School of Civil and Mechanical Engineering

Developing an Integrated Framework to Assess the Sustainability Potential of Alternative Fuels - A Life Cycle Approach

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This thesis is presented for the degree of
Doctor of Philosophy
of
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To my parents, all the teachers in my life & beloved wife, daughter, and son!

Declaration

To the best of my knowledge and belief, this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Human Ethics (For projects involving human participants/tissue, etc): The research presented and reported in this thesis was conducted in accordance with the National Health and Medical Research Council National Statement on Ethical Conduct in Human Research (2007) – updated March 2014. The proposed research study received human research ethics approval from the Curtin University Human Research Ethics Committee (EC00262), Approval Number # HRE 2019-0101 and # HRE 2019-0642.

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Abstract

The increasing concerns about climate change, dwindling nature of fossil fuels and fuel security issues are demanding fuel supply solutions that are environmentally friendly, socially acceptable and economically competitive. Consequently, the researchers and practitioners have intensified their focus on finding alternative fuels for the transport sector.

The literature on alternative fuels is predominantly aimed at assessing the environmental impact of fuels using the environmental life cycle assessment (ELCA) methods and frameworks. Most of the existing strategies and frameworks lack assessment of the economic viability and social acceptability of alternative fuels. There is limited research on the economic and social assessment of fuels. Furthermore, the existing studies on the sustainability assessment of fuels are constrained to assessing the environmental, economic and social aspects independent of each other. These deficiencies lead to difficulties in conducting a realistic assessment of the sustainability performance, which is crucial for making decisions about the selection and adoption of alternative fuels.

A careful consideration of the interdependencies of the environmental, economic and social aspects of fuels is a fundamental requirement for a realistic assessment of the sustainability of fuels. Incorporating the region-specific data, such as the energy-mix, geographical conditions, and local government policies/incentives into the assessment framework is an extremely important as well as essential requirement for a more accurate assessment of the sustainability performance of alternative fuels.

In this study, a life cycle sustainability assessment (LCSA) framework has been developed. The framework provides a comprehensive platform for an integrated assessment of the environmental, economic and social impact of alternative fuels using the principles of life cycle assessment and triple bottom line (TBL). In the first phase, it utilizes a rationale for selecting the potential fuels and the TBL indicators for further investigation. It is followed by the environmental life cycle assessment of the selected fuels. The ELCA results are compared with a pre-defined threshold value, and a fuel proceeds to the social impact assessment phase only if it meets the threshold. For the fuels that don’t satisfy the threshold, improvement strategies are incorporated and the ELCA is redone. The social life cycle assessment (SLCA) phase assesses the social viability of the fuel by assessing its performance against the social indicators. The social impact assessment results are compared with pre-defined threshold values before proceeding to the economic assessment. Similar to the ELCA phase,

improvement strategies are incorporated and the SLCA is reassessed if a fuel fails to meet the threshold. The final stage of the assessment is the life cycle costing (LCC). This stage also utilizes the threshold criteria for comparing and identifying the fuels that are economically viable. Like the previous two stages, improvement strategies are incorporated and the LCC is redone if a fuel fails the LCC threshold criteria. A fuel that satisfies the environmental, social and economic criteria is recommended for use.

The framework was employed to assess the sustainability potential of ethanol-gasoline blend E65 (65% ethanol and 35% gasoline), electricity, electricity-gasoline hybrid and hydrogen as alternatives to gasoline. These fuel options were chosen based on the fuel-selection criteria that considers the availability of resources, such as feedstocks for production of the fuels in Western Australia (WA). The data for the environmental, social, and economic assessment was collected from the local stakeholders, and also through literature review, supply chain analysis, expert opinion and surveys.

The initial assessment indicated that none of the four selected fuel options had met the minimum requirements for the predefined sustainability criteria as defined by the corresponding threshold values. Then, different improvement strategies, such as using renewable energy in the production of alternative fuels, utilizing by-products, introducing financial incentives for the production of alternative fuels, providing subsidies to promote the use of vehicles that use alternative fuels, local manufacturing of the batteries, establishing infrastructure to facilitate the recharging of batteries were incorporated and the fuels were reassessed. The fuel option E65 failed to meet the land use criterion. Thus, E55, which met all the environmental criteria, was proposed. After incorporating the strategies, the reductions of GHG emission for BEV and PHEV were found to be around 50% and 35%, respectively. Regarding environmental and social assessment, the hydrogen fuel showed the best performance among the analysed fuel options when renewable electricity was considered for the production of hydrogen. It resulted in around a 69% reduction in GWP and about a 65% reduction in the FFD indicator compared to gasoline due to replacing current fossil-based electricity with wind and solar energy. However, the economic sustainability of hydrogen was uncertain, mainly due to the high cost of the hydrogen fuel cell vehicle (around 2.5 times higher than gasoline). The results of the iterative analysis revealed that the environmentally friendly, socially sustainable and economically viable adoption of E55, electricity, and hybrid electricity-E10 with 90% gasoline and 10% ethanol would require 0.02, 0.14 and 0.10 AUD financial support per vehicle kilometre travelled (VKT), respectively, to be comparable with gasoline.

The proposed LCSA framework has been successful in comprehensively addressing the impact of the interdependences among the various TBL indicators for the sustainability assessment of alternative fuel options. The results are deemed reliable as well as realistic because the framework considers the region-specific environmental, social and economic conditions. The study provides essential data to assist decision-makers concerned about the selection and adoption of alternative fuels for the transport sector.

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"In the name of Almighty Allah, the most beneficent, most gracious, the most merciful".

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Glossary

AFCP	Alternative Fuel Conversion Program
AHP	Analytical hierarchical process
ALCAS	Australian Life Cycle Assessment Society
AUD	Australian Dollar
AusLCI	Australian life cycle inventory
AVMC	Additional vehicle material cost
BEV	Battery electric vehicle
BP	British Petroleum
CFF	Conservation of fossil fuel
CML	Life cycle assessment method developed by the Institute of Environmental Sciences of the University of Leiden
CNG	Compressed natural gas
CRC	Carbon reduction credit
CSIRO	The Commonwealth Scientific and Industrial Research Organization
CV	Co-efficient of variance
E2	Ethanol-blended gasoline (2% ethanol and 98% gasoline)
E55	Ethanol-blended gasoline (55% ethanol and 45% gasoline)
E65	Ethanol-blended gasoline (65% ethanol and 35% gasoline)
E85	Ethanol-blended gasoline (85% ethanol and 15% gasoline)
EIOLCA	Economic input output life cycle assessment
ELCA	Environmental life cycle assessment
EU	European Union
FFD	Fossil fuel depletion
FU	Functional unit
g	Gram
GDP	Gross domestic product
GHG	Greenhouse gas
gmt	Green metric tonne
GST	Goods and service tax

GV	Gasoline vehicle
GWP	Global warming potential
ha	Hectare
ha.a	Hectare.annum
HFCV	Hydrogen fuel cell vehicle
HH_{VEE}	Human health based on vehicle exhaust emission
IEA	International Energy Agency
ILCD	International life cycle data
IPCC	Intergovernmental Panel on Climate Change
ISO	International standard organization
kg	Kilogram
KIA	Kwinana Industrial Area
L	Litre
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory
LCSA	Life cycle sustainability assessment
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LU	Land use
MAVT	Multi attribute value theory
MCDA	Multi criteria decision analysis
MJ	Megajoule
ML	Megalitre or Million litre
Mt	Mega tonne or Million tonne
NiMH	Nickel metal hydride
ODP	Ozone depletion potential
OECD	Organisation for Economic Co-operation and Development
OHAS	Occupational health and safety
PEM	Proton exchange membrane

PHEV	Plug in hybrid electric vehicle
PJ	Petajoule
PM	Particulate matter
PPA	Power purchase agreement
PV	Photovoltaic
PROSUITE	Prospective sustainability assessment of technologies
SDG	Sustainable development goal
SETAC	Society of Environmental Toxicity and Chemistry
SHDB	Social hotspot database
SLCA	Social life cycle assessment
TBL	Triple bottom line
tkm	Tonne-kilometre
UNEP	United Nations Environmental Program
VKT	Vehicle kilometre travelled
WA	Western Australia
WC	Water consumption

List of Publications

Published Journal Papers:

1. Najmul Hoque, Ilyas Mazhar and Wahidul Biswas. Application of life cycle assessment for sustainability evaluation of transportation fuels. Encyclopaedia of Renewable and Sustainable Materials, Materials Science and Materials Engineering, 2020, 4, 359-369.
2. Najmul Hoque, Wahidul Biswas, Ilyas Mazhar and Ian Howard. LCSA framework for assessing sustainability of alternative fuels for transport sector. Chemical Engineering Transactions, 2019, 72, 103-108.
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4. Najmul Hoque, Wahidul Biswas, Ilyas Mazhar and Ian Howard. Life cycle sustainability assessment of alternative energy sources for the Western Australian transport sector, Sustainability, 2020, 12(14), 5565.
5. Najmul Hoque, Wahidul Biswas, Ilyas Mazhar and Ian Howard. Sustainability implications of using hydrogen as an Automotive fuel in Western Australia, Journal of Energy and Power Technology, 2020, 2(3), 1-17.

Conference Presentation:

N Hoque, WK Biswas, I Mazhar, I Howard. LCSA framework for assessing sustainability of alternative fuels for transport sector. Presented in the 4th International Conference on Low Carbon Asia & Beyond – ICLCA, 24-26 October 2018, Johor Bahru, Malaysia.

Statement of Contribution and Declaration of Co-Authorship

I hereby declare that I have authored and co-authored the publications used in this thesis. The level of my intellectual input for all the publications is 80%. Signed verification statements from each of my co-authors are for all the publications provided in **Appendix-A** of this thesis.

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Chapter 1

Introduction

The thesis presents the development and application of an integrated Life Cycle Sustainability Assessment (LCSA) framework to assess the environmental, social and economic impact of alternative fuels using a life cycle approach. The proposed methodology has been developed to assess the sustainability of potential alternative fuel options for the car dominant transport sector in Western Australia (WA). To achieve this research goal, the existing literature was explored, TBL indicators were developed through a consensus conference involving local experts, and data collection and analysis were conducted using the sustainability assessment tools.

1.1 Background

With the development of quality of live and human desires, secure and reliable energy supply has become an essential requirement for modern humanity. The use of the World's primary energy increased around 15% in 2018 from the level of 2010 (BP, 2019) and this usage is also projected to grow 50% by 2050 from the 2010 level (US Energy Information Administration, 2019). Research indicates that around 80% of the global primary energy consumption is from fossil fuels, and 58% of this is in the transport sector (Hoque et al., 2019a). The transport sector is consuming a substantial share of energy in countries around the World. The energy consumption from the transport sector, for example, is about 28%, 27% and 31% of the total energy respectively in USA, Australia and EU countries (Department of the Environment and Energy, 2017; European Environment Agency, 2017; United States Environmental Protection Agency, 2020).

The transport sector is already consuming more than half of the global oil production in 2012 (IEA, 2012) and this could be around 88% in 2040 (U.S. Energy Information Administration, 2016). Extensive use of various fuels is not only resulting in the depletion of resources, but it is also increasing the concerns regarding energy security and environmental damage. The transport sector in Australia, for instance, heavily relies on liquid petroleum fuels (Hoque et al., 2019a). The country could face serious energy security issues if there is a substantial fluctuation in price and/or geopolitical conflicts due to the fact that more than 90% of its transport fuel is imported from different conflicting zones (Blackburn, 2014; Farrell, 2017). The strategic petroleum reserve of Australia is also quite low compared to other Organization for Economic Co-operation and Development (OECD) countries (Commonwealth of Australia, 2019). The country holds only around three weeks cover of its liquid fuel requirements (Commonwealth of Australia, 2019; Hoque et al., 2020a). The sector was responsible for about 16% of the total Australian GHG emissions in 2016. This over-dependence of fossil fuels, resources crunch, and climate change issues stress the necessity for alternative transport fuels to meet the needs and expectation of the current generation without compromising the ability of future generations to fulfil their needs.

The environmental, economic and social implications need to be assessed and addressed before implementing any initiatives for sustainable fuel development. An approach that addresses these three aspects of sustainability has been documented as a triple bottom line (TBL) analysis (Hall, 2011; Santoyo-Castelazo and Azapagic, 2014). It takes into account environmental, economic and social impacts for sustainability assessments. The TBL sustainability analysis of fuel, however, remains incomprehensive without consideration of the life cycle assessment (LCA) approach (Hoque et al., 2019b). The LCA technique considers cradle to grave analysis of a fuel, demonstrates the complete picture and interprets the results to find the hotspot for proper policy formulations to achieve sustainability objectives. Life cycle sustainability assessment (LCSA) approach which integrates the TBL objectives and considers the whole life cycle of a product is an effective tool in this regard (Hoque et al., 2020a; UNEP, 2011). The LCSA comprises of environmental life cycle assessment (ELCA), life cycle costing (LCC) and social life cycle assessment (SLCA) under the identical system boundaries (UNEP, 2011).

1.2 Problem statement

Research indicates that the existing LCA studies on alternative fuels mainly focus on the environmental life cycle assessment (ELCA) (Hoque et al., 2020b). The assessment of alternative fuels needs to be considered based on strong sustainability principles, considering the triple bottom line (TBL) aspects of sustainability that includes not only the environmental objectives but also the social and economic aspects. Especially, incorporation of the SLCA with the other two dimensions is quite limited due to the lack of methods (such as indicator selection process, impact assessment and scenario analysis) and unavailability of data (Akber et al., 2017). Preliminary concept has already been discussed by the UNEP but more practical case studies that integrate these three sustainability assessment tools are required (Hoque et al., 2019b). To ensure improved sustainability assessment, the TBL indicators and the pertinent data quality also needs to be reflective of the local perspectives (Hasan et al., 2020; Petti et al., 2018). For example, geographically large countries like Australia, USA and Canada have a number of states or provinces with varied climatic zones and socio-economic differences, and so it may not be realistic to apply the LCA results of one state to the other because of the widely dispersed nature of the energy-mix and environmental conditions (Hoque et al., 2020b). The assessment approach needs to incorporate the strategies that are appropriate for the region. Besides, a holistic sustainability assessment framework needs to be capable of incorporating both quantitative and qualitative indicators (Keller et al., 2015). Most of the exiting life cycle sustainability assessment tools for alternative fuels did not adequately address following areas:

(i) comprehensive assessment considering life cycle approach and TBL objective of sustainability
(ii) consideration of the regional perspectives, such as the development of TBL indicators and sustainability threshold based on local needs
(iii) incorporation of suitable strategies which can be achievable for a region to attain TBL sustainability thresholds
(iv) demonstration of inter-relationship (For example, change in social and economic sustainability due to any change in environmental or vice versa) between the three objectives of sustainability.

Mining which is the life blood of WA's economy has the same energy consumption (239.7 PJ, 22.36%) as the transport sector (230.7 PJ, 21.5%) (Hoque et al., 2020a). About 78% of WA's vehicles are passenger cars of which 87% use imported gasoline. This is because the people in WA are heavily dependent on passenger cars and the public transport are not popular due to dispersed population centres (Biswas et al., 2013; Hoque et al., 2019a). Even within Perth, travelling by passenger car in 20 minutes often takes more than an hour by public transport that includes buses, trains and ferries (Wynne E, 2017). WA's transport fuel contributes quite a large share (14%) of the state's GHG emissions (Biswas et al., 2013). Low elevation vehicle exhaust emissions in the atmosphere also have the potential to cause significant human health problems (Renouf et al., 2015). The use of locally available alternative fuels needs to be explored for the passenger vehicles in WA to overcome the aforementioned socio-economic and environmental issues. A few studies have been conducted on alternative fuels for WA (Ally and Pryor, 2016; Biswas et al., 2013) but they lack incorporation of the TBL approach and improvement strategies.

Therefore, for effective decision making, a holistic sustainability assessment framework is required to measure the sustainability performance of alternative fuels with particular emphasis on a region-specific condition (Hoque et al., 2019b; Hoque et al., 2020b). This study is thus, aimed at developing a comprehensive framework to assess the sustainability potential of alternative fuels. The proposed framework has been tested using the Western Australia (WA) data because WA is one of the car-dominant states in Australia (Hoque et al., 2019a). A range of strategies have also been employed to improve the sustainability performance of the selected fuel options.

1.3. Research objectives

Alternative fuels are required to be assessed in the perspective of the three dimensions of sustainability. The sustainability assessment of alternative fuels remains incomplete without life cycle assessment. This research is focused on developing a comprehensive framework using a life cycle assessment approach for assessing the sustainability performance of alternative fuels for the passenger car dominant transport system in Western Australia (WA). The findings of the review of the literature have led to the following research objectives.

Objective 1: *Investigating the application of life cycle approach for the sustainability assessment of alternative fuels and identifying the deficiencies in the existing methods and frameworks. Developing an integrated framework that overcomes the identified deficiencies and difficulties in the current approaches.*

A comprehensive review of the literature on ELCA, SLCA and LCC of alternative fuels has been conducted to investigate the strengths and weaknesses of the existing assessment approaches. The publications (Hoque et al., 2020b and Hoque et al., 2019b) provide a detailed discussion on the findings of the review. These publications also discuss the developed framework.

Objective 2: *Exploring the various fuel options for the transport sector with particular emphasis on Western Australia.*

Identifying the potential alternative to gasoline is one of the primary goals of this study. The WA transport sector has been chosen as a case study for this purpose. The focus is on passenger vehicles because about 78% of WA's vehicles are passenger cars of which 87% use imported gasoline. The alternative transport fuels for diesel were not within the scope of the study. Another constraint on the fuel aspect of the study is the locally available feedstocks/resources needed for the production of alternative fuels. The selected fuel options for the assessment are ethanol-gasoline blend E65 (65% ethanol and 35% gasoline), hydrogen, electricity for battery electric vehicles (BEV) and electricity-gasoline for plug in hybrid electric vehicles (PHEV).

A detailed discussion on fuel selection is in the author's publications (Hoque et al., 2019a and Hoque et al., 2020a) and also in the associated supplementary material.

Objective 3: *Assessing the sustainability performance of the selected fuel options.*

Defining the TBL indicators for the three pillars of sustainability, collecting the data, conducting the analysis are the predominant aspects of this phase of the study. The assessment utilizes 11 indicators to conduct the ELCA, SLCA and LCC. Surveys, expert opinion and a rigorous review of the literature are the basis for the identified indicators that take into account the region-specific conditions. The results of the assessment are in the author's publications (Hoque et al., 2019a; Hoque et al., 2020a and Hoque et al., 2020c).

Objective 4: *Exploring various strategies to improve the sustainability performance of different fuels based on the predeveloped threshold values.*

Devising rationale for the comparative analysis is an essential requirement for recommending a fuel as an alternative to gasoline.

For this, threshold values have been developed by analysing the information that was acquired through surveys, expert opinion and literature review. The developed threshold values serve as the minimum performance level for further analysis, or for recommending the fuel as an option. This is also crucial for identifying a fuel as a candidate for further performance enhancement through improvement strategies. The author's published work (Hoque et al., 2020a) demonstate this aspect of the research.

1.4 Research methods

The study includes a review of the literature, development of a framework, fuel selection, identification and selection of indicators, development of threshold values, and data collection. It is followed by the environmental life cycle assessment (ELCA), social life cycle assessments (SLCA) and Life cycle costing (LCC) of the selected fuels.

An extensive review of the literature on ELCA, SLCA and LCC and TBL sustainability assessment is crucial for ascertaining the state-of-art of sustainability assessment of alternative fuels. This has helped to understand the strengths and potential of the existing methods and frameworks. It has also been critical in identifying the areas for further improvement.

Conducting surveys, acquiring the stakeholders' views, and obtaining expert opinion are the methods used for collecting data for various phases of the life cycle assessment of fuels. This has been done to ensure that the proposed framework is comprehensive as well as capable of addressing the local and region-specific conditions. The gathered information has been used to identify and select the TBL indicators for the study and also used to establish the threshold values for the indicators. The surveys have been conducted in accordance with the Guidelines by the Curtin University Research Integrity Committee (approval number: HRE 2019-0101). For the qualitative data (e.g. Occupational Health and Safety indicator for this study), a consensus survey (Curtin University Human Research Ethics Committee approval number: HRE 2019-0642) has been conducted based on a 5-point Likert scale where 5 is the threshold value (Hoque et al., 2019b; Lim and Biswas, 2019) to qualify as a sustainable option.

The data collection and environmental impact assessment have been performed as per the ISO guidelines (ISO14040, 2006; ISO14044, 2006). The LCA software Simapro 8.4 has been used to process the data. The LCC has been conducted based on AS/NZS 4536:1999 guidelines using a discounted cash follow analysis.

1.5 Significance

This study provides a realistic and comprehensive basis for decision-making on the selection and adoption of alternative fuels. The proposed LCSA framework overcomes the deficiencies in the existing methods of sustainability assessment of fuels. The developed framework fulfils the need for a robust tool for capturing and incorporating the geographical and socioeconomic interdependencies into the sustainability assessment of alternative fuels. The study provides a crucial platform to practitioners and policymakers to devise the energy policies that are environmentally friendly, socially acceptable and economically competitive.

1.6 Limitations of the research

Some of the limitations of the research are as follows:

- The TBL indicators and threshold values used in the study may change over time due to changes in government policies and/or socio-economic circumstances. Future studies need to take this into account.
- Currently, there are no supply chains for alternative fuels in the WA. Therefore, this study employs some representative data from other Australian states and socioeconomic regions like EU countries and USA.
- The threshold value technique is employed in the framework as a decision context of sustainability. One of the limitations of the threshold value technique is that there is no

additional worth of product (i.e., fuel in this study) if any calculated value scores more than the threshold value.

- Enviromental emission and cost data for wheat based ethanol have been collected from a medium yield paddock of WA Wheatbelt. The total wheat plantation area in WA is around 5 million hectares (Wilkinson, 2018). Medium yield paddock is selected as it requires average inputs of fertilizers and chemicals. Variation of emission with the different paddocks is out of the scope of the study.
- The data for vehicle exhaust emission (e.g., exhaust emissions for ethanol, gasoline and plug in hybrid vehicles) has been acquired from various sources. Measuring the real emission data for WA is also beyond the scope of this research.
- As the supply chains for alternative fuels are still in the development/implementation stage, securing and using the real data pertaining to the indicator, 'Occupational Health and Safety' is not possible. Therefore, representative data has been used.

1.7 Thesis outline

Figure 1.1 shows an outline of the thesis. It contains seven chapters that have been organised in the form of research publications.

Chapter 1 provides the background, problem statement, research objectives and scope of the study. It also highlights the research methods, limitations and significance of the research.

Chapter 2 presents the findings of the review of the literature on existing methods for the life cycle assessment of alternative fuels. It helps in building a foundation for the proposed LCSA framework.

Chapter 3 illustrates the development of the framework that incorporates the environmental, social and economic aspects of fuels.

Chapter 4 demonstrate the process for the selection of alternative fuels for assessment. The factors, such as the availability of feedstock and other resources required for the production of alternative fuels have been explained in this chapter.

Chapter 5 demonstrates the environmental life cycle assessment of the selected fuels. The chapter also includes the local indicator selection for ELCA.

Chapter 6 illustrates the final phase of the assessment. It presents the SLCA and LCC of fuels and demonstrates the use of threshold values. It also illustrates the impact of the suggested improvement strategies to improve the sustainability performance of the alternative fuels.

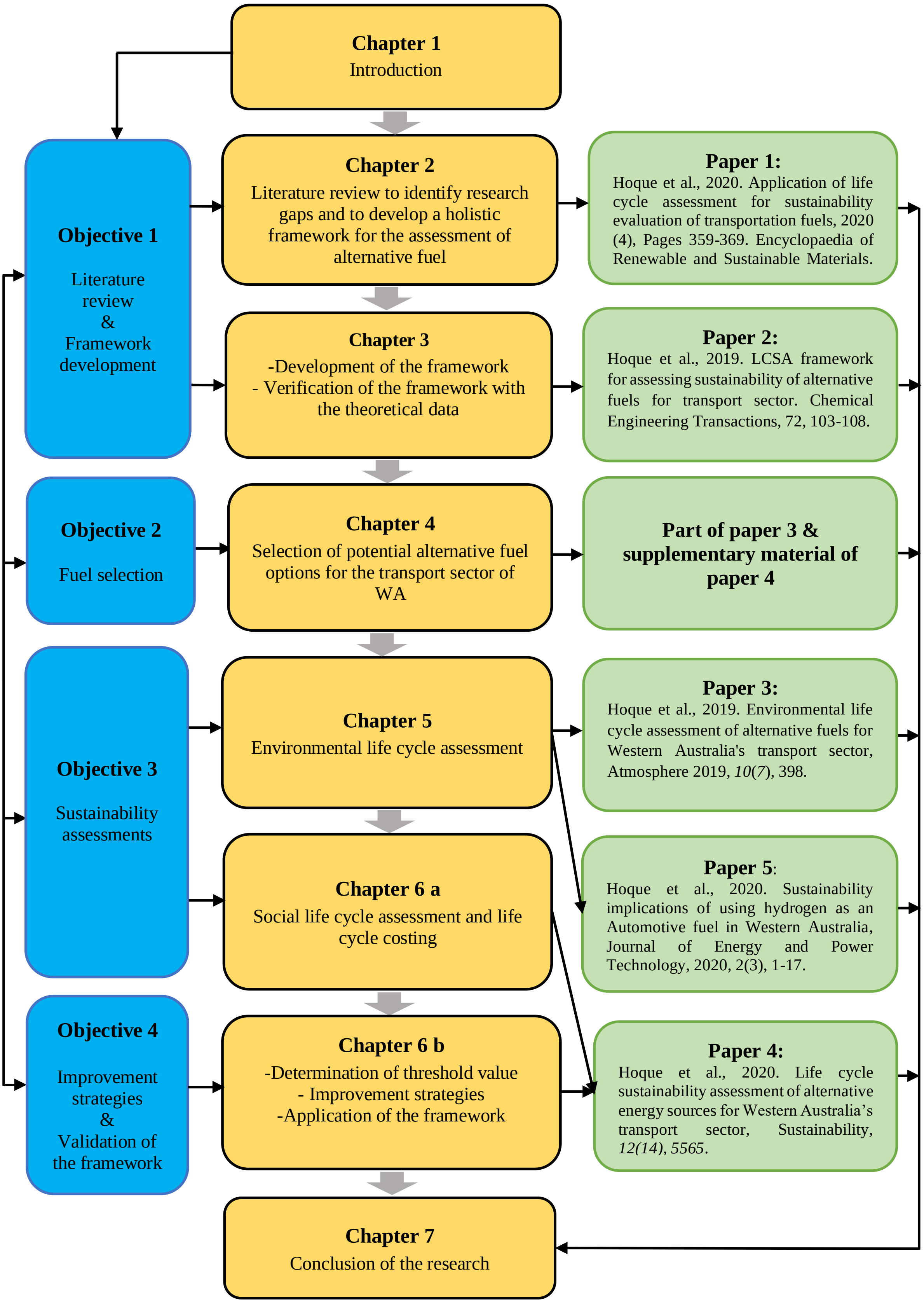

Figure 1.1: Publications and Outline of the PhD thesis

Chapter 7 summarises the outcomes of the research.

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Chapter 2

Literature Review

This chapter (Page number 12 to 36 of the thesis) has been removed due to copy right issue. A brief summary of the chapter is as follows:

It is evident in the from the studies that there is a research gap within life cycle assessment from the perspective of TBL sustainability assessment of alternative transport fuels. More holistic frameworks and practical case studies are required to conduct LCSAs that will reflect all three aspects of sustainability as well as follow the guidelines of LCA adequately. Both fuel cycle and any associated change in the vehicles due to use of alternative fuels need to be considered within the system boundary to examine the whole life cycle impacts. Best practice LCA guidelines for a particular country or region should be adopted to alleviate the dissimilarities of assessment procedures among LCA practitioners. It was observed that authors quite often selected sustainability indicators from previous literatures and internationally agreed guidelines which literally did not reflect the actual scenario of particular regions. Due to these reasons, selection of triple bottom line indicators and impact assessment should be in line with the best practice guidelines of a particular country/region and should reflect the scenarios of the region. Possible scenario analysis will also be required to cover future cases. The required number of impact categories and indicators should be devised based on a region/country as it changes with location and places. As of now, mostly MCDA techniques were used to integrate the triple bottom line impacts of ELCA, LCC and SLCA. More novel methods and techniques which are capable of handling both qualitative and quantitative outcomes are needed to assess sustainability hotspots of fuels. It is, thus, necessary to develop threshold values for sustainability assessments for each alternative fuel for a particular region for sustainability assessment. The threshold values for the environmental, economic or social score of a particular fuel in fact represent the best or sustainable practice. Based on the review, it is also found that there is a need to conduct LCA regionally to obtain a better sustainability outcome as the LCA result of one region cannot be used in another region due to the data variability. Therefore, more region wise LCAs should be conducted for informed decision-making processes.

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Chapter 3

The Framework to Assess the Sustainability of Alternative Fuels

Abstract

Consideration of alternative transport fuels produced from locally available feedstocks and renewable resources is important for enhancing energy security and alleviating environmental burdens. Whilst these fuels are apparently considered to be clean, they may not be entirely sustainable from economic, environmental and social perspectives. A Life Cycle Sustainability Assessment (LCSA) framework that integrates all three components of Triple Bottom Line (TBL) sustainability can potentially be used to evaluate the sustainability performance of fuels from well to wheel. This chapter presents an LCSA framework consisting of Environmental Life Cycle Assessment (ELCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA) tools to assess the environmental, economic and social performance of alternative fuels. The framework is aimed at identifying the areas that require improvements for overall sustainability performance. The proposed framework provides a comprehensive basis that considers the region-specific variations in the life cycle data pertaining to alternative fuels. The added feature of the framework is its robustness to accommodate variations in natural resources, and other regional issues, such as socio-economic and demographic changes. The framework has been tested using a hypothetical example of canola-based biodiesel.

3.1 Introduction

Use of alternative transport fuels is emerging as one of the potential strategies to achieve energy security and alleviate environmental consequences. The selection of an alternative fuel depends on the ability to produce it from locally available feedstocks and renewable resources. The increased demand for fossil fuels will result in resource depletion, health impact and environmental issues (Kumar et al., 2018). Fuels for the transport sector thus need to be sourced in a manner that allows resource efficiency and conservation of fossil fuels for future generation (Sebayang et al., 2017). Alternative fuels need to be analyzed and selected to address the environmental, social and economic challenges to ensure that the transportation industry becomes sustainable. The TBL sustainability assessment method that integrates the environmental, economic and social objectives could be used to select alternative fuels (Hall, 2011). The TBL sustainability analysis remains incomprehensive if it does not include the entire life cycle of a product or service. LCSA incorporates all the three components of the TBL (ELCA, LCC and SLCA), and considers a cradle to grave approach (Ciroth et al., 2011) that generates more realistic as well as comprehensive outcomes. Research indicates that ELCA has been the most widely applied tool for assessing environmental impacts, while quite a few studies have employed LCC and SLCA along with ELCA. Like ELCA, SCLA follows the four steps, goal and scope, life cycle inventory, impact assessment and interpretation of results, to measure the social impacts caused to stakeholders during the product life cycle. The impacts of SLCA may not be discussed in the context of the functional unit as most of its data will be qualitative or semi quantitative (Ciroth et al., 2011). SLCA is a bit complicated as it is based on indicators and expert opinion that may vary across regions due to variations in the socio-economic and cultural issues (Mathe, 2014). Given the absence of region specific TBL assessment, utilizing all three Life Cycle Assessment (LCA) tools for alternative fuel selection, the current research endeavors to develop the sustainability assessment framework using a LCA approach.

3.2 LCSA frameworks for alternative fuels

The UNEP-SETAC has developed a guideline to integrate the ELCA, SLCA and LCC into the LCSA that evaluates environmental, economic and social impacts of a product throughout its life cycle under an identical system boundary (Ciroth et al., 2011). Guinee et al. (2011) describes the LCSA through a conceptual framework combining ELCA, LCC and SLCA by emphasizing the need for LCSA for encompassing people, planet and prosperity. Zamagni et al. (2013) states that LCSA is still at a conceptual level and so there is a need for frameworks with practical case studies to make the LCSA usable. By summarizing all the challenges in LCSA, Guinée (2016) points out that there is a need for practical case studies with efficient ways of communicating the LCSA results and method. There are not many studies that have considered the LCSA approach for investigating the alternative fuels. Onat et al. (2014), for instance, conducted a LCSA study of alternative fuels using an EIOLCA (Economic Input Output LCA) model for different alternative fuel vehicle types in the USA. The main concerns about using EIOLCA is that its evaluation is based on the transactions of a particular economy, and it is not very suitable for a region specific product level analysis (EIOLCA, 2017). Onat et al. (2016) employed a dynamic model that was only applicable to the US based economy. In another study, Osorio-Tejada et al. (2017) employed the Analytical Hierarchy Process (AHP) for Multi Criteria Decision Making (MCDM) to evaluate the TBL aspects of biodiesel and LNG use as a transport fuel in Spain, but only the GHG emission indicator out of the nine TBL indicators was found, calculated based on the LCA approach. The SLCA requires that both upstream and downstream processes and people are involved in the analysis to carry out a holistic and realistic assessment. The LCSA application in the sectors other than fuels also lacks a uniform and consistent approach when it comes to defining the parameters such as goal and scope definition, impact assessment and interpretation of results. Akber et al. (2017), for instance, conducted a comprehensive study regarding the Pakistan electricity sector by considering the cradle to grave approach but faced a constraint regarding social data and methodology which necessitated the selection of social indicators only related to employment and energy security. The study considered the ELCA indicators based on the CML (Life cycle assessment method developed by the Institute of Environmental Sciences of the University of Leiden) impact assessment method which ignored local perspectives. The equal weighting method was also employed in the study to produce single score results for all three sustainability dimensions rather than using other appropriate weighting methods. Santoyo-Castelazo and Azapagic (2014), on the other hand, overcame the weighting issues by applying stakeholders' opinion and scenario analysis based on different weighting approaches though it was focused only on the electricity generation phase. Though these studies used MCDM techniques to combine TBL indicators based on different weightings, the scenario analysis related to interdependencies among the three pillars of sustainability was missing.

In conclusion, the reviewed sustainability assessment frameworks demonstrate no uniform or consistent approach to define the system boundary when they conduct the LCA, LCC and SLCA in the context of the LCSA. The other challenges include difficulties in interpreting and communicating the results, and scenario analysis incorporating interdependencies among the three pillars of sustainability as well as data quality that needs to account for regional perspectives and methods for SLCA (Guinée, 2016). Most importantly, alternative fuels have not been found to be rigorously assessed in the context of the TBL indicators where their impacts conform to the LCA guidelines (Onat et al., 2016) and there is a need for a robust framework for the sustainability assessment of various fuel options.

3.3 The proposed framework for LCSA

A sustainability assessment framework that employs the ELCA, LCC and SLCA tools to measure the TBL performance of alternative fuels is shown in **Figure 3.1** and has been discussed in the following sections.

3.3.1 Fuel selection

The first step involves alternative fuel selection for a particular region or country. Accordingly, the relevant literature has to be reviewed based on the vehicle types and availability of resources for a region to supply required alternative fuels.

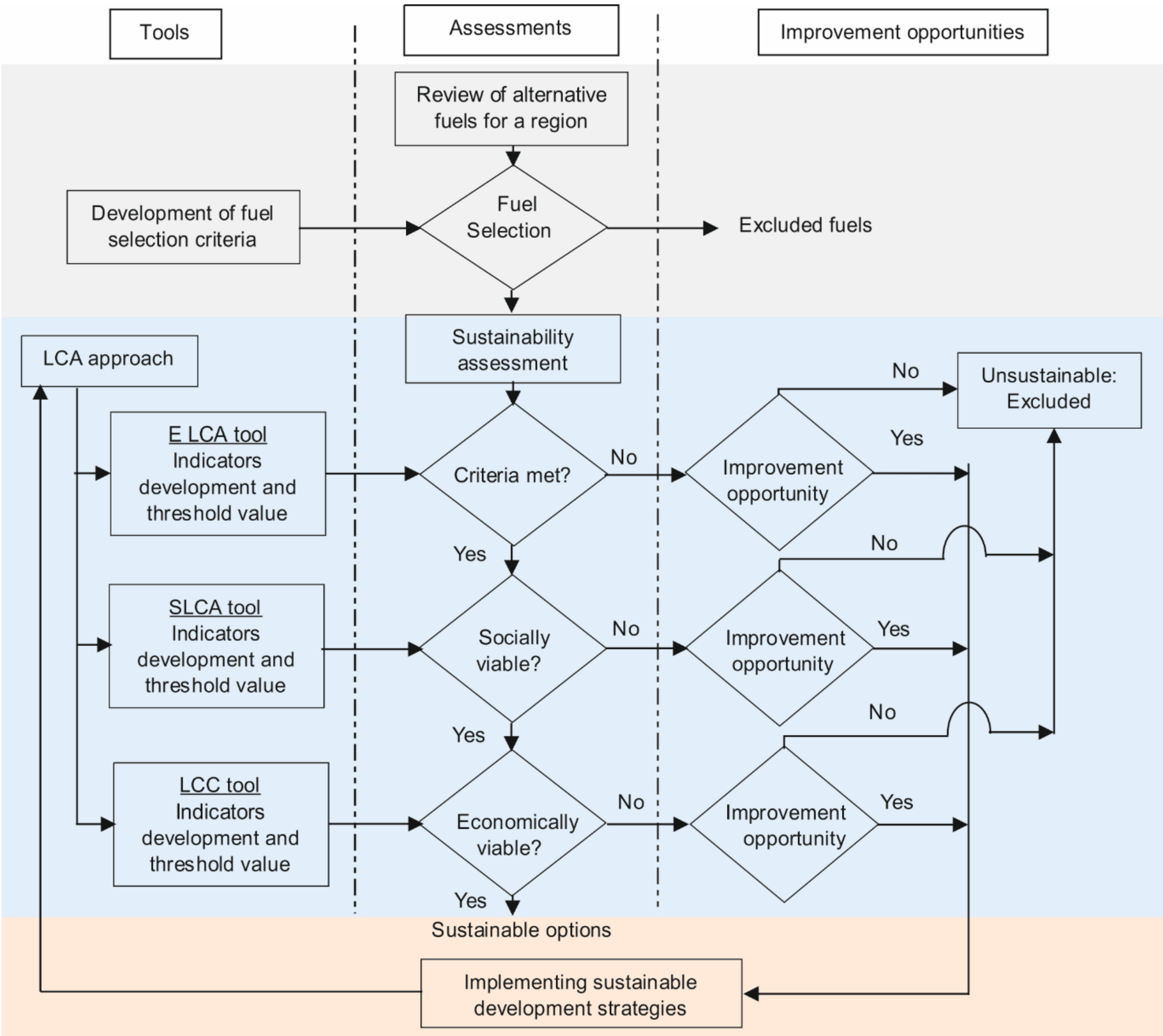

Figure 3.1: Holistic sustainability framework for LCSA to assess the alternative transport fuel

3.3.2 Selection of TBL indicators and the determination of threshold values

The next phase of the framework is intended to review the literature to list the relevant TBL indicators that are used to reflective of the social, economic and environmental performance of the transport fuels using an LCA approach. Once the list of indicators has been prepared, a census is conducted to ascertain the views of the stakeholders who are directly related to the production, use, business, technology and policies associated with the transport fuels. For example, the stakeholders are grouped into three categories namely government, industry and academia with each respondent category consisting of equal number of respondents to avoid any bias. The survey helps in selecting the appropriate TBL indicators. Once the TBL indicators have been selected, it is required to find the threshold values for comparing them with the real data obtained from the field/case studies. The threshold values are used in the framework as a decision context of sustainability. The threshold values are chosen realistically so that they are achievable in the fuel sectors in a particular region while maintaining standard fuel supply. For the framework, the standard fuels are defined on the assumptions that they have locally available feedstock and follow reasonable environmental and socio-economic obligations during fuel production and combustion. A thorough literature search and consultation with the local experts are required to discern these threshold values for comparison with calculated values obtained from the field data. Fuel option will undergo for social screening once all the environmental indicators meet the criteria i.e., threshold values. There will be no additional value of scoring more than the threshold when threshold value technique is used as selection criteria (Sala, 2015). Similarly, economic analysis is allowed only when all the environmental and social criteria are met. The framework follows the strong sustainability principle where environmental constraints guide the economic activity without compromising societal benefits (i.e., environmental gets priority followed by social and economic) (Janjua et al., 2019; *Lim et al., 2015*).

3.3.3 Data collection

Once the indicators have been developed, the data for the environmental, social, and economic assessment is required to be collected from the local stakeholders, and also through literature review, supply chain analysis, expert opinion and surveys.

3.3.4 Life cycle assessment tools

Once the raw data has been gathered, the environmental, economic and social indicators of sustainability are calculated using the ELCA, LCC and SLCA tools, as indicated in the left column in Figure 3.1. ELCA follows the ISO14044 guidelines to estimate the environmental indicators (ISO14044, 2006). Accordingly, a functional unit, which is Vehicle Kilometers Travelled (VKT) is chosen to calculate the inputs and outputs for well to wheel stages, including feedstock production, fuel production and usage stage of the fuel life cycle for developing a life cycle inventory prior to calculating the environmental indicators. In the next stage, the relevant impact assessment method(s) are selected for the analysis. The Australian indicator method, for example, can be used for converting inventory data to environmental indicators if the evaluation is done in Australia. LCC analysis, on the other hand, follows the same inventory and functional unit as ELCA to calculate the economic indicators following the AS/NZS 4536:1999 guidelines (Australian and New Zealand Standard, 1999) in terms of $/VKT. Life cycle cost and cost/VKT are some examples of economic indicators. Discounted cash flow analysis needs to be included in the analysis by considering inflation, and discount rates. Government subsides, if any, also need to be included in the analysis to make it more realistic.

Social LCA can be carried out based on the UNEP-SETAC guideline. Social indicators are selected depending on the interaction between the life cycle activities and people involved. These indicators can be selected from the literature and the globally accepted guidelines published by UNEP-SETAC, IPCC, SDG, IEA, OECD and various government and semi government reports relevant to the selected region. Getting the expert opinion is the next logical step to establish the relevance of the selected indicators. This facilitates the process of assessing and addressing the social implications associated with various fuel types.

3.3.5 Application of the proposed sustainability assessment framework using a hypothetical case study

Following Figure 3.1, the first step is to determine the environmental indicators of the selected fuel using an ELCA tool. Examples of environmental indicators that are relevant to this research are Energy Consumption (EC), Energy Ratio (ER), Global Warming Potential (GWP), Eutrophication, and Ozone Layer Depletion (ODP), etc. These environmental indicators are selected randomly for this hypothetical case to apply the LCSA framework before actual case study (chapter 5 and 6). Once these indicators have been determined for a fuel type, they are compared to their threshold values to examine if the required level of environmental performance has been achieved. A fuel type is declared as “not qualified” for social assessment if it fails to meet its threshold value. The hotspots that are identified in the ELCA analysis would be treated using improvement strategies until all environmental indicators have met the threshold values. Once environmental criterion has been met, SLCA would be conducted to determine social indicators. Some examples of social indicators are employment generation, public health, and social acceptability, etc. Similar processes as discussed before would be carried out by developing social strategies, and institutional arrangements that enable the selected fuel type to meet the social objectives of sustainability. LCC of the fuel type is carried out to ascertain the economic indicators like life cycle cost, cost/VKT etc. If economic indicators have not met the threshold values, policy instruments like capital subsidy, rebates, and soft loans, etc. can be considered to achieve the required economic objectives.

A hypothetical example of canola-based biofuel has been used to test the sustainability assessment framework. The indicators that were chosen for this example are assumed. The purpose is to demonstrate the functioning of the proposed framework. The following discussions are thus fictitious, and they have been described in way that they were based on a real-world data which is actually not the case. The system boundary for this LCA analysis to estimate social, economic and environmental indicators started from the farming stage of the feedstock through to combustion in the vehicle and the functional unit is VKT. As shown in **Table 3.1**, EC, ER and GWP are three environmental indicators that the authors intend to collect through surveys. When these indicator values were compared with the threshold values none of them was found to meet the environmental objectives. The threshold values are chosen for this study by reviewing the works of Biswas et al. (2011) and Rustandi and Wu (2010). The threhold values are conisdered based on standard fuel supply as mentioned in section 3.3.2.

Table 3.1: Evaluation of the environmental sustainability

Indicators	Calculated value	Threshold value	Values after Improvement Strategies		
			1	2	3
EC* (MJ/VKT)	2.33	≤1.52	1.71	1.49	1.20
ER**	1.13	≥1.72	1.53	1.76	2.20
GWP+ ($KgCO_{2-eq}$/VKT)	0.27	≤0.19	0.191	0.164	0.105

*Life cycle energy consumption of fuel per VKT, **Ratio of energy output and input of fuel required per VKT
+Life cycle global warming potential of fuel per VKT

Through an LCA analysis, a hotspot has been identified to determine the environmental improvement of mitigation strategies. The hotspot analysis shows that the fertilizers, herbicide and pesticide production during pre-farm and biodiesel production during post-farm stages are the two main energy intensive processes. Unlike energy consumption and energy ratio, the on-farm stage was responsible for the highest global warming potential mainly due to the soil emission from fertilizers. Three improvement strategies as shown in Table 3.1 have therefore been selected to treat the energy and GHG hotspots. These are i) by-product utilization, ii) both by-product and straw utilization and, iii) crop rotation with by product and straw utilization in order to reduce energy consumption and GHG emission associated with the production and application of urea fertilizer. Here, canola meal and glycerol are considered as by-products which reduce both energy and environmental burden on overall biodiesel production. Straw was considered as a replacement for diesel for process heating during ethanol production. The second and third environmental improvement strategies helped all environmental indicators to meet the threshold values.

SLCA of canola-based biodiesel that has incorporated the aforementioned environmental strategies into its supply chain have been conducted to determine social indicators using the same system boundary. As mentioned during the ELCA analysis, this hypothetical example was provided to test the framework. In practice an actual survey will be required to collect the sample data from the respondents as shown in chapter 5 and 6. Three social indicators including employment generation, public health and social acceptability need to be measured on a 1 to 5-point Likert scale on the basis of the respondents' level of satisfaction. The score 5 represents the maximum level of satisfaction and the respondents not giving a score of 5 have been asked to provide suggestions/improvement strategies that would have completely satisfied the respondent. **Table 3.2** shows that out of the three indicators, only public health had met the highest level of satisfaction (i.e., 5). In the case of employment generation, 40% of the respondents did not score 5 as they would like more local people to be employed which is not possible immediately and requires long term planning (strategy to improve job creation) . The remaining 20% who did not score this indicator 5 had expressed that it is difficult for a new fuel industry to generate employment quickly. More than 70% of the respondents scored 5 for the public health indicator in this example by assuming the fact that biodiesel significantly reduces all the tail pipe emissions and could enhance the public health condition. In the case of social acceptability, 45% of respondents did not score 5 as there was no significant promotional campaign for public awareness (strategy to improve social acceptability) of the benefits of biodiesel and also there was not enough incentive to encourage users. The remaining 25% believed that biodiesel would not be socially acceptable due to its higher price and availability issues. On the basis of respondents' suggestions, possible improvement strategies for social indicators have been considered. In the case of employment generation, employment of local people appears to be achievable with long-term planning, as well as an awareness campaign and incentives to popularize biodiesel could easily be executed to improve the social acceptance. As shown in **Table 3.2,** the incorporation of these strategies could achieve the social objectives of sustainability.

Table 3.2: Example of evaluation of the social sustainability

Indicators	Surveyed value	Threshold value (% of the respondent provides maximum score)	Values after improvement Strategies
Employment generation	40 %	≥50%	(40 % + 40 %) or 80 %
Public health	71 %		-
Social acceptability	30 %		(30 % + 45 %) or 75 %

Using the same boundary as ELCA and SLCA, LCC per VKT has been calculated, as shown in **Table 3.3** with the hypothetical values. The costs and benefits associated with the newly incorporated environmental and social strategies have been incorporated into the cost of inputs of the existing life cycle inventory for LCC analysis. Threshold values have been chosen based on the current diesel price in Western Australia. Still, the life cycle cost of biodiesel did not meet the threshold values.

Table 3.3: Evaluation of the life cycle cost

Indicators	Initial calculated value	Threshold value	Values after improvement strategies	
			After by product and straw utilization	After providing rebate
life cycle cost (AUD/VKT)	0.189	≤0.115	0.116	0.114

On this basis, another strategy has been deployed to make the fuel economically viable, which is the removal of excise duty on biodiesel. Prior to 2011 in Australia, full excise on biodiesel was refunded to the biodiesel producers by the biofuel production grant mechanism. According to the revised policy of the Australian government, the current excise rate is 0.027 AUD/L of biodiesel (Farrell, 2017). After incorporating this economic strategy, the fuel was able to meet the economic objective of sustainability. Further reduction of LCC can be possible if external costs, such as a carbon reduction cost is implemented by the government.

3.4 Conclusions

A holistic LCSA framework has been developed to identify and select improvement strategies to enable alternative fuels to meet the environmental, social and economic objectives. It involves the development of the TBL indicators and their threshold values using literature and surveys. Once the indicators have been selected, raw data from the supply chain of alternative fuels would be gathered to calculate the TBL indicators for assessing the sustainability and suggesting improvement strategies. A hypothetical example has been used to test the framework. A LCA approach has been applied to calculate the indicators. The proposed framework has been shown to be robust and has been demonstrated to accommodate various scenarios more comprehensively.

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Chapter 4

Fuel Selection

4.1 Introduction

Region specific fuel selection for a location, is the first step in the framework, which entirely depends on the availability of the relevant feedstocks. There could be sustainability benefits of sourcing feedstocks locally as it creates local employment and avoids cost and emissions associated with transporting these feedstocks. The transport sector of Western Australia (WA) is passenger vehicle dominant as around 78% of vehicles in WA are passenger cars. Around 87 % of those passengers' vehicles are using gasoline as fuel. Due to the dominance of gasoline vehicle in the state, there is a need to look out for suitable alternatives to gasoline. Keeping in mind the availability of resources in WA, alternative fuel options, such as E65 (ethanol-gasoline blend: 65% ethanol), electricity for battery electric vehicle (BEV), electricity-gasoline for plug-in hybrid electric vehicle (PHEV), and hydrogen were selected for the analysis in this chapter as alternatives to gasoline. For the ethanol fuel (E65), three potential feedstocks, namely, wheat (10%), cereal straw (53%), and mallee (2%) were considered.

4.2 Basis of selection

Gasoline is the predominant transport fuel type in Australia. Around 75% of vehicles in Australia were passenger cars and 87% of those uses gasoline as fuel (Australian Bureau of Statistics, 2017c). The registered passenger vehicles, in 2017, in Australia consumed around 19,486 Megalitres (ML) of fuel (Australian Bureau of Statistics, 2018). In 2017, Australia was already importing around 90% of its liquid fuel, and it is predicted that it could be close to 100% by 2030 due to the closures of more refineries in the country (Blackburn, 2014; Farrell, 2017). This may end up with an energy scarcity issue, as the fluctuation of price, and geopolitical conflicts in fossil fuel supply have been experienced a number of times over the recent decades (Hoque et al., 2019a).

Western Australia is one of the private car dominated states in Australia. Public transport is not very popular in WA due to the dispersed locations and long distances between the population centres. As like the overall Australian scenario, around 78% vehicles in WA were passenger cars and 87% of those vehicles were using unleaded gasoline. There were also approximately 17% light commercial vehicles in the state, and 37% of those were dependent on gasoline

(Hoque et al., 2020b). Total amount of gasoline sold in WA was 2262 million litres (ML) in 2017 (Department of the Environment and Energy, 2017b). Almost 100% of WA's transport fuel comes from non-renewable fossil sources and around 97% of which is the imported liquid fuel (Hoque et al., 2019a). With gasoline as the dominant transport fuel, around 14% of GHG emissions of WA were from the transport sector (Hoque et al., 2019a). The government was, however, committed to maintain a GHG emission reduction of 26–28% below the 2005 level by 2030 (Shahiduzzaman and Layton, 2015).

It appears that the current and future trends of private/passenger car which dominate the transport sector in WA could suffer from energy security issues and environmental consequences (Hoque et al., 2019a). Due to the quite high percentage of passenger vehicles in the state, there is an urgent need for the WA to consider suitable alternatives to gasoline (Hoque et al., 2019a, 2020a). Therefore, the fuel alternatives to gasoline that are suitable for passenger vehicles are considered in the study. It is necessary to consider the availability of feedstocks to produce the required amount of alternative fuels for a region (Balat and Balat, 2009; Farine et al., 2012; Hoque et al., 2019a, b). Balat and Balat (2009), for example, stated that sources of feedstocks and their long-term availability to produce alternative fuels are quite crucial for any country/region as additional environmental impacts and cost would be incurred if the feedstock was imported from other regions. Farine et al. (2012) also supplemented that the availability of feedstocks locally is necessary for the sustainability of alternative fuel as the import of feedstock from other regions would bring back the fuel security issues. This chapter discusses the availability of potential local resources in WA to produce alternative fuels that are suitable for gasoline passenger vehicle.

Different types of alternative fuels that are investigated for passenger vehicles as an alternative to gasoline are ethanol, biogas (Sadeghinezhad et al., 2014), electricity (Hawkins et al., 2013), CNG (Khan et al., 2015; Raslavičius et al., 2014), LPG (Khan et al., 2015; Raslavičius et al., 2014), and hydrogen (Biswas et al., 2013). Methanol has not been considered for the investigation in this study as its use for motor vehicles has almost been phased out due to its lower caloric value (almost half of the gasoline) and potential safety hazards (Agarwal, 2007; Bergthorson and Thomson, 2015). Besides this, liquified natural gas (LNG) is also not included in the discussion as this fuel is mainly suitable for heavy propulsion engines, such as ships, trucks and buses (Osorio-Tejada et al., 2017; Pfoser et al., 2018; Qingfang et al., 2013; US Department of Energy, 2018). Section 4.3 describes the available feedstocks for the production of ethanol fuel for WA. It is followed by a discussion related to other fuels, such as electricity, natural gas, biogas and hydrogen in WA.

4.3 Ethanol

Ethanol (CH_3CH_2OH) as a replacement for gasoline is quite popular as it can be produced from a variety of local resources (Alternative fuel data center, 2019), and it is also compatible with the internal combustion (IC) engines (Thangavelu et al., 2016). This section presents a summary of the potential of ethanol as an alternative to gasoline based on the feedstock's availability in WA.

4.3.1 Potential of ethanol as an alternative fuel for gasoline passenger vehicles in WA

Australia produces quite a low amount of biofuel compared to Europe and USA (Farine et al., 2012). Commercial ethanol production plants in Australia are shown in **Table 4.1**. There are mainly three commercial ethanol production plants in Australia, which are situated in Queensland (QLD) and New South Wales (NSW) (Farrell, 2017). Wheat, sorghum and sugarcane molasses are used as feedstocks for those three plants. The Manildra plant in NSW is the biggest ethanol production facility in the country and produces 300 million litres of ethanol per year from wheat grain. Whereas, Dably bio-refinery owned by United Petroleum (sorghum based) and Sarina distillery (sugar cane molasses) are producing 80 ML and 60 ML of ethanol per year, respectively, in QLD. Australian ethanol production was estimated to be low due to the low gasoline price, subsequent low demand, higher feedstock cost and unfavourable policy frameworks (Farrell, 2017). In 2016, for example, average ethanol sale in NSW was 2.6% and the mandated 6% ethanol use in NSW was never fulfilled.

Table 4.1: Ethanol Plants in different states in Australia

Plant	Location	Total installed Capacity (ML/year) *	Feedstock*
Dalby Bio-Refinery operated by United petroleum	QLD	80	Sorghum
Manildra Ethanol Plant	NSW	300	Wheat starch
Sarina Distillery by Wilmar	QLD	60	Sugar cane molasses

*Based on Rural Industries Research and Development Corporation (2018).

In Western Australia, there are no commercial ethanol plants though there are several potential feedstocks available in the state. Currently, it is quite hard to find ethanol in WA as well (AECOM Australia, 2016; Fuel Watch Western Australia, 2020). The sources of ethanol production can be subdivided into two main groups; starch (e.g., wheat, corn, sorghum, etc.) and sugar (e.g., Sugarcane) based feedstocks, and cellulosic based feedstocks (e.g., wood chips or crop residue) (Alternative fuel data center, 2019). Suitability of potential feedstocks for ethanol production in WA are discussed below:

Starch and sugar-based feedstocks:

Around 50% of the Australia's total wheat is produced in WA. WA has a long history of producing wheat. Though WA's rain-fed wheat production has fluctuated a bit over the years due to the weather, overall increasing trend of wheat production was found since 1980 (Wilkinson, 2018). In 1980, the overall wheat production in WA was around 1.5 million tonnes which increased to around 10 million tonnes in 2010, and this value was hovering around 10 million during the last 5 years (Wilkinson, 2018). Around 95% of the wheat grain produced in WA is exported under the WA government's contracts mainly with several Asian countries (Hoque et al., 2019a). The allotment of the remaining 5% of wheat for ethanol production could potentially affect the local requirement (Hoque et al., 2019a). Around 0.57 Million tonnes of wheat have been estimated to produce about 228 ML ethanol (**Equation 4.1**) to generate E10 (**Equation 4.2**) without affecting the food supply (Hoque et al., 2019a)**.** Wheat farmers can also enjoy competitive advantage due to the allotment of this amount of wheat for alternative fuel (GRDC, 2019). This 228 ML has been estimated to be the substitution to 6.6% of gasoline in WA based on the lower calorific value of ethanol (**Equation 4.3**). This small portion of wheat for ethanol may not affect the food supply chain as only the starch part of wheat is required for ethanol production and the remaining amount (around 80%) goes back to the food cycle as wet distiller grains (Hoque et al., 2019a).

$$Amount\ of\ ethanol\ prodcution\ from\ feedstock = \\ Amount\ of\ ethanol\ from\ per\ unit\ feedstock \times Amount\ of\ available\ feedstock \quad (4.1)$$

$$Possible\ ethanol\ blend\ from\ feedstock = \\ Amount\ of\ ethnaol\ production\ from\ feedstock \div Gasoline\ requirment\ of\ WA \quad (4.2)$$

$$Percentage\ of\ gasoline\ replacement\ in\ WA\ due\ to\ ethanol\ production = \\ Ethanol\ blend \div \left(\frac{Calorific\ value\ of\ gasoline}{Calorific\ vlaue\ of\ ethanol}\right) \quad (4.3)$$

The following values are used to calculate equation 4.1, 4.2 and 4.3 for wheat-based ethanol:

Amount of wheat = 0.57 M tonnes

Ethanol conversion rate from wheat = 400 L/tonne (Muñoz et al., 2014)

Gasoline requirement of WA = 2262 ML (Department of the Environment and Energy, 2017b)

Ratio of calorific of gasoline to calorific value of ethanol = 1.51 (O'Connell et al., 2007)

Barley is the second major grain product of WA. Out of 7.5 million tonnes of total Australian barley production, 3.5 million tonnes are produced in WA, and 85% of those goes to international export markets (Government of Western Australia, 2018). WA's barley is exported to China, Japan, Kuwait, South Africa, South Korea, and UAE. The remaining small fraction (0.5 million tonnes) is consumed in the state, which is not sufficient to be allotted for ethanol production. Barley produced in the other states in Australia is also consumed as food (Barley Australia, 2017). Barley is also not widely used for ethanol production in the World due to its abrasive hull that is destructive for grain handling equipment, low starch content compared to corn and wheat, and high viscosity of mash due to beta-glucans. Due to these reasons, ethanol from barley is expensive compared to wheat (Hicks et al., 2018; Nghiem et al., 2010).

Corn, grain sorghum and sugarcane are the other three popular sources of ethanol in the World but the production of those feedstocks in WA is not popular due to the unfavourable climatic conditions (AgriFutures Australia, 2017; Hoque et al., 2020a). These feedstocks are also insufficient in amount for ethanol production in the other parts of Australia (AECOM Australia, 2016; Hoque et al., 2020a).

Cellulosic feedstocks

Among the second-generation sources, cereal straw and mallee tree are the two prospective sources of ethanol production in WA (Hoque et al., 2019a, 2020a). The estimation of the available straw for ethanol production takes into account the following considerations:

- Total non-grain biomass was 3.24 tonnes/ha (Stucley et al., 2012) based on average grain production of 1.8 tonnes/ha in WA (Wilkinson, 2018),
- Around 1.5 tonnes/ha was retained on the grain field to prevent soil erosion and enrich soil organic content (Stucley et al., 2012),

- The average maximum cutting height from soil is 20 cm that does not go further due to the unevenness of the grain field (Stucley et al., 2012),
- Two locations (Albany and Three springs) were not considered due to the low resource availability of straw to fulfil the requirements for the plant.

The estimated amount of straw is 5,157 × 10^3 tonnes (**Table 4.2**), the ethanol blend that can be considered with this amount of ethanol is E53 based on the **Equation 4.1, 4.2 and 4.3** as follows:

Ethanol blend = (5157/4.32) ÷ (2262*1.51) ≈ 35% gasoline replacement ≈ E53 (35X1.51)

Where, the straw requirement for per litre of ethanol is 4.32 kg based on the 25% moisture content (Hoque et al., 2019a; Mu et al., 2010).

This E53 could potentially generate ethanol to substitute 35% of gasoline in WA based on **Equation 4.3**.

Table 4.2: Estimation of straw for ethanol

Potential locations	Average straw after 1.5 tonnes retention (tonne/per ha)	Land area[+] (ha × 10^3)	Available straw on grain field (Value* 10^3 tonne)
Geraldton	(3.24* − 1.50) = 1.74	267	465
Three springs		85	148
Moora		425	740
Northam		337	586
Merredin		365	635
Lake Grace		304	528
Narrogin		200	348
Katanning		526	915
Esparance		541	941
Albany		67	116
Total		3112	5421

[+]Based on the straw availability by Brooksbank et al. (Brooksbank et al., 2014),

*Average non-grain biomass 3.24 tonne/ha (Stucley et al., 2012).

There is also a huge potential to grow mallee in between the long narrow belt of agricultural fields in WA without affecting the current farming practices. Apart from its use as a biofuel, there are several co-benefits as it reduces dryland salinity and waterlogging; prevents soil erosion from wind; and protects biodiversity (Stucley et al., 2012; Wu et al., 2007). Mallee trees could provide WA's national fuel security and increase the benefit to the farmers (Stucley et al., 2012). Around 10% of the area of the WA wheat belt (around 830,000 ha) can supply 10 million gmt (green metric tonne) of woody biomass (URS Asutralia, 2008). It has been found that framers are willing to take economic advantage through mallee production if there is a demand in the market. It is believed that mallee production might be increased if the WA government declares a future mandate regarding ethanol. Current available resources of mallee (around 0.259 Mt) (Hoque et al., 2019a; John and Amir, 2011) can generate 1.3% of gasoline replacement in WA (Hoque et al., 2020a). This available resource could produce an ethanol blend approximately equivalent to E2 (based on **Equation 4.1, 4.2 and 4.3**). There are several potential sites, such as Katanning, Narrogin, Kulin, Merredin, Wagon hills, Dalwallinu, Moora and Three Springs that have already been identified as the potential sites for mallee processing plants in WA based on the availability of mallee plantings and grid electricity (Oil Mallee Association Australia, 2019).

Ethanol blend from mallee = (0.259*1000/5.80) ÷ (2262*1.51)

≈ 1.3% gasoline replacement ≈ E2 (1.3X1.51)

Where,

Ethanol conversion rate from mallee= 5.80 kg/L (Hoque et al., 2019a; Mu et al., 2010)

Based on these resources' availabilities, an ethanol-gasoline blend E65, which consists of 10% wheat based, 2% mallee based and 53% straw-based ethanol (i.e., E53 from cereal straw, E10 from wheat and E2 from mallee wood), is considered for this study. Forrest residues, as a feedstock, are not considered for ethanol production in WA due to the highly distributed nature of the feedstocks making their collection time consuming and expensive (Department of Primary Industries and Regional Development, 2018; Farine et al., 2012; Hoque et al., 2020a).

4.3.2 Summary

The following conclusions have been drawn:

- WA produces around 10 million tonnes of wheat, of which 95% is exported. Around 0.57 million tonnes of wheat have been estimated to produce about 228 ML ethanol to generate E10 without affecting the food supply.

- Except for wheat, WA also produces 3.5 million tonnes of barley and around 85% of this is exported to the international market. Keeping in mind the domestic market demand, the remaining amount (0.5 million tonnes) is not sufficient to be used for ethanol production. Also, barley cannot be imported from other states of Australia as most of the produced amount is consumed as food. Besides, barley is also not widely used for ethanol production in the World due to its abrasive hull which is destructive for grain handling equipment, low starch content compared to corn and wheat, and high viscosity of mash due to beta-glucans.
- WA climatic conditions are not supportive of growing sugar cane, corn and sorghum. These feedstocks also cannot be brought in WA from other states of Australia for ethanol production because transporting the required quantity, which is very small, is not economically viable.
- Among the second-generation sources, cereal straw and oil mallee are the two potential options for WA. The estimated amount of straw is $5,157 \times 10^3$ tonnes that could potentially supply E53 (35% gasoline replacement considering the lesser caloric value of ethanol compared to gasoline as shown in equation 4.1) for the state. The current mallee resources (around 259×10^3 tonnes), on the other hand, could potentially supply E2.
- Based on the resource's availabilities, an ethanol-gasoline blend E65, which consists of 10% wheat based, 2% mallee based and 53% straw-based ethanol, is considered for this study.

4.4 Electricity

Electricity is being considered as one of the promising alternatives to gasoline as electric vehicles may meet the requirements for a passenger vehicle in respect to load, range, and purpose (Ally et al., 2015). This section describes the suitability of electric vehicles in WA.

4.4.1 Opportunities of using electric vehicle in WA as an alternative to gasoline passenger vehicle

Australia has lots of renewable resources, and especially almost all the states have the potential of adequate solar and wind-based electricity generation (Bahadori et al., 2013; Hydrogen Strategy Group, 2018; Shafiullah et al., 2012). That means electric vehicles can be powered by comparatively cleaner electricity in the country, which can also help the nation to meet its Paris emission reduction agreement goals (Climate Works, 2017). Though there are potential benefits, only around 73,500 electric vehicles were sold in the Australian market from 2011 to 2017 (Climate Works, 2018). In 2017, the number of electric vehicle sales was only 2,284 in Australia, which represented 0.2% of the total Australian vehicle sales (Climate Works, 2018). Among these, there were 1,076 Plug in hybrid electric vehicles (PHEV) and 1,208 were battery electric vehicle (BEV) (Climate Works, 2018). The traditional hybrid cars are out of the scope of this study as those are often excluded during counting or reporting of electric vehicles as gasoline is the only fuel for this car (Climate Works, 2017, 2018; IEA, 2017). The description of BEV, PHEV and traditional hybrid cars are provided in **Appendix-B**. It has been found that the higher initial cost of electric vehicles is the main barrier to the uptake of electric cars in Australia. Different projections, however, indicate that the electric vehicles will account for 15% to 45% of all light vehicle sales in Australia by 2035 (Climate Works, 2017).

There were around 475 electric vehicles sold in Western Australia between 2011 and 2017, which was 0.06% of total vehicle sales in 2017 (Climate Works, 2018). WA has the potential to install electric vehicle charging facilities even at home or apartments (Jeisman, 2018). To promote the electric vehicles, a subsidized home charging electricity plan during off-peak hours for BEV and PHEV is available in WA (Synergy, 2019). Electric vehicles in WA can also be charged in the car parks of offices and shopping centres as the state has the benefit of having large parking spaces (Mader and Braunl, 2013). The fast charging stations can also be built along WA highways for long holiday tours. The Royal Automobile Company (RAC), for example, in collaboration with the local government has built 11 such DC charging stations for demonstrations in different locations of WA (RAC, 2018). The number of electric vehicles uptake in WA has been forecasted to be around 10.5%-34% of all vehicles in 2036 (Operator, 2016). Therefore, there could be around 204,100 (if 10%) to 693,041 (if 34%) electric vehicles in WA by 2036.

The electricity generation mix in WA is comparatively cleaner (**Table 4.3**) than the other states of Australia by comprising 53% natural gas-based and around 7.1% renewable energy-based (mainly solar and wind) electricity (Hoque et al., 2019a). Whereas, the percentage of electricity produced from coal in Victoria, NSW and QLD was 85%, 82%, and 65%, respectively. Future energy policy of WA also supports the initiatives of electric cars as penetration of more renewable energy in WA's grid is inline according to the policy of Western Australian Government (Department of Finance Public Utilities Office, 2012; Western Australian Planning Commission, 2014). It has been estimated that around 37% of the electricity would be produced from renewable energy by 2030 in WA (Hoque et al., 2019a; The Climate Institute, 2009). In total, 2829 MW of total commercial renewable electricity is possible in WA by 2030, which was only 286 MW in 2010 (The Climate Institute, 2009). This expected renewable energy scenario is favourable for electric vehicles in WA. It has also been estimated that Western Australia is capable of meeting almost all of its electricity and energy needs from renewable resources by properly utilizing its solar and wind energy potential (Laslett et al., 2017; Lu et al., 2017). Lu et al. (2017), for example, estimated that integration of solar, wind and pumped hydro (to store excess wind energy) could produce almost 100% of WA's renewable electricity. Recently, the Australian Capital Territory (ACT) demonstrated an example of almost 100% renewable electricity in the state with the household cost saving by using market deregulation through innovative contracts and agreement with the utilities and users (Mzengrab, 2019).

The use of electric vehicles may also be promoted by encouraging off-peak recharging (Mullan et al., 2011). Ally et al. (2015) stated that electric vehicles are a suitable alternative to light-duty gasoline passenger vehicle based on the load, range, and purpose. Electric vehicles do not require new infrastructure as electricity networks are already well established. It has been investigated and shown that the current electricity grid in WA has a significant amount of surplus that could accommodate as much as 200,000 (10% of all vehicles of WA) vehicles (Hoque et al., 2019a, 2020a). This leads to more investigations into environmental, economic and social aspects of electric cars (BEV and PHEV) for devising and implementing policies for enhancing the use of electric vehicles in the state.

Table 4.3: Electricity generation mix in WA

Feedstocks/sources	In GWh	In percentage
Natural gas	20146	53%
Coal	10523	28%
Oil products	4223	11%
Biogas	126.9	0.34%
Wind	1643.2	4%
Hydro	206.1	1%
Solar PV	683.3	2%
Total	37552	100%

4.4.2 Summary

Below is a summary of the facts about the potential utilization of electric vehicles in WA:

- The number of electric vehicles uptake in WA is expected to increase 10.5% -34% by 2036.
- Environmental performance of electric vehicles depends on the sources of electricity that is used for charging. The electricity generation mix in WA is comparatively cleaner than the other states of Australia. WA's energy policy also supports the use of electric cars as penetration of more renewable energy in WA's grid are also inline as indicated in the energy policy. It has been estimated that around 37% of electricity will be produced from renewable energy by 2030 in WA. Almost 100% renewable based electricity would also be possible in WA without increasing the cost.
- The use of electric vehicles may be promoted by encouraging off-peak recharging. Charging facilities could be built in houses and apartments for overnight charging. The current grid in WA has a significant amount of surplus which is enough to support up to 200,000 (10% of total WA vehicle) electric vehicles.
- Thus, a viability assessment is required to know the actual environmental, economic and social benefits of using electric vehicles in WA. Keeping in mind their potential, battery electric and plug-in hybrid electric vehicles (BEV and PHEV) are considered for assessment in this study.

4.5 Compressed natural gas (CNG) and Liquified petroleum gas (LPG)

Both CNG and LPG originated from fossil fuels (John, 2019). The CNG is basically a pressurised form of natural gas (CH_4) that mainly contains methane. It is usually stored in cylinders at a pressure of around 20 MPa (2900 psi) for vehicle use. LPG, on the other hand, is a mixture of propane and butane. LPG is produced mainly as a by-product during the production of petroleum oil. Some LPG is also extracted in petroleum refineries during the production of refined products, such as gasoline, diesel, kerosene, etc., from crude oil. The pressure of LPG cylinders (320 psi) is relatively lower compared to CNG. These two gases are usually discussed and reported together due to their similar nature of use in vehicles (Energy Supply Association of Australia, 2014; Raslavičius et al., 2014). This section presents a summary of the potentiality of these gases as vehicle fuel in WA.

4.5.1 Potential of CNG and LPG as an alternative to gasoline for passenger vehicles in WA

During 2014-15, around 66,421 million cubic meters of natural gas has been produced in Australia. Around 61% of the natural gas in Australia is used for LNG exports. Other than LNG export, electricity generation and industrial applications are the major natural gas consuming sectors in Australia. Even though some vehicles were converted to gas vehicles in Australia, the uptake of gas vehicles has come to a complete stop after the subsidies were withdrawn. Only a few buses and light commercial vehicles (around 3,000) in Australia use CNG (Australian Bureau of Statistics, 2017b; NGV global, 2018). The uptake of these CNG vehicles was seen through the Alternative Fuel Conversion Program (AFCP) toward commercial vehicles over 3.5 tonnes by Australian Greenhouse Office in 2000. The AFCP used to provide a grant to cover the half of the additional cost of new CNG vehicle compared to traditional counterpart or conversion of an existing vehicle to gas, but the program ran only until 2004 (Energy Supply Association of Australia, 2014). The progress was halted after the termination of the AFCP grants. The dispersed nature of Australian cities, insufficient infrastructures to support CNG as a transport fuel, changes in the government policy due to small GHG emission benefit compared to liquid fuel, deregulation and privatization of the gas utilities and investment decision towards LNG were the key drivers to stop the AFCP grants (Gas Today, 2009; Hoque et al., 2020a).

Besides, only a small amount (3,687.5 ML in 2016-17) of LPG is produced in Australia. In the year 2016-17, Australia also imported an additional 958.5 ML of LPG to meet its demand. The production rate of the naturally occurring LPG in Australia has shown a long-term declining trend (Department of the Environment and Energy, 2017a). Due to the closure of the oil refineries in Australia, the refinery produced LPG is also reduced drastically. In total, the amount of LPG production in Australia has reduced by around 30% in 2017 compared to 2011. In Australia, LPG is used mainly as a fuel in industry and household purposes (Roarty and Rann, 2001). Australia can survive for 59 days only with its current LPG reserve (Hepburn, 2018; Hoque et al., 2020a). In 2006, the Australian Government declared a LPG scheme that provided AUD 1000 rebate to the customer to convert their car to LPG or AUD 2000 to purchase new LPG vehicle. With the introduction of that scheme, there were around 314,000 cars retrofitted to gasoline-LPG in Australia. The backward trend of LPG vehicles, however, has been started due to the termination of the retrofitting scheme in 2014 and introduction of a fuel excise on LPG. Insufficient local production, high cost of LPG conversion, the increase of LPG price, and a lack of refuelling infrastructures has hampered the LPG growth in Australia (Energy Supply Association of Australia, 2014; Hoque et al., 2020a).

In Western Australia (WA), CNG is not available in the refuelling stations (Fuel Watch Western Australia, 2020). The CNG is used only in 365 public buses operated by WA's metropolitan public transport authority (Transperth). Transperth, however, has their own refuelling station in their bus depots to refuel those buses (source: communication with Transperth). LPG is, however, available in some refuelling stations within the Perth metropolitan region, but is quite limited outside the metropolitan of Perth (source: communication with the Fuel Watch Western Australia), but the census of the LPG-based passenger vehicles was disregarded due to the lower number of LPG vehicles in WA (Energy Supply Association of Australia, 2014). The foreseeable causes of unsuitability of CNG and LPG as potential alternative transport fuels in WA are described below:

- Western Australia (WA) is the major natural gas producing states in Australia. Sixty-nine percent of Australian natural gas is produced in WA, and the remaining 31% is accounted for by all other states. WA also contains 92% of the total gas reserve of Australia. There are 148,144 Peta joules (PJ) of conventional and another 187,699 to 295,864 PJ (1PJ=0.027 billion cubic meters of natural gas) of shale and tight gas reserve in the WA and it has been estimated that the state can run another 97 years from now if it consumes the gas in the same manner as at present. Though there is nothing wrong with these forecasts, only 73,913 PJ of these reserves are the proved and probable reserves which can run out very quickly (by 2045, i.e. 26 years from now) (AEMO, 2017; Hoque et al., 2020a).
- WA is already in a long-term contract with serval international companies to export LNG and 97% of WA’s conventional gas reserves are held by the LNG export companies and their joint ventures (Hoque et al., 2020a).
- The WA government has introduced a policy to supply only 15% (around 217 PJ) of its natural gas (of equivalent LNG production) to the WA domestic market (AEMO, 2017; Hoque et al., 2020a). Among the WA domestic sectors, around 47% gas is consumed (**Table 4.4**) for electricity generation, 48% is used by the industrial and mineral sectors, and the remaining 5% is consumed for other domestic and commercial purposes (AEMO, 2017). It has also been forecasted that the domestic gas supply of WA would fall by 3.5% in 2022 compared to 2018 though a minor increase (0.3%) of the demand is expected. This is mainly because of the expiry of the contacts with a few companies and uncertainty of the supply of gas from 2022 due to the reserve depletion in a few gas production facilities (AEMO, 2017). An additional 83.78 PJ (**Equation 4.4**) of gas would be required per year to replace all the gasoline in WA, which is not available at the moment in the domestic market (Hoque et al., 2020a). To save the WA gas for

electricity generation, household and industrial application seem to be better options than its use for transportation (Hoque et al., 2020a).

$$Natural\ gas\ requirement\ of\ WA\ in\ PJ\ per\ year\ to\ replace\ all\ the\ gasoline\ requirement\ in\ WA,$$
$$= (2262 \times Z) \div (1000 \times 0.027) \tag{4.4}$$

Where,

The gasoline requirement of WA= 2262 ML/year,

Constant 1000 to convert 2262 million L to billion L,

Z = 1, which is the equivalent amount of natural gas in m^3 to replace 1 L of gasoline (Han, 2018; Hoque et al., 2020a) and

1 PJ = 0.027 billion cubic meters of natural gas (AEMO, 2017)

Table 4.4: Gas uses in domestic sectors of WA

Sectors	Gas used (%)
Electricity production	47%
Industrial	29%
Residential and commercial	3%
Mining	19%
Other	2%

- Besides, only a small portion of LPG is produced in WA, which is not enough to be a potential alternative fuel for WA transport sector (Hoque et al., 2020a). According to the Department of Mines Industry Regulation and safety, only 22.50 PJ of LPG (≈ 800 ML) was produced in WA in 2017 (Department of Mines Industry Regulation and safety, 2018). LPG is used for industrial, commercial and household applications in WA. A trivial amount of LPG is also used in the transport sector. Based on the total gasoline requirement for WA and the mileage of LPG cars (20% less than the gasoline), it can be calculated that around 2714 ML of LPG (**Equation 4.5**) would be required to replace all gasoline in WA (Hoque et al., 2020a). So, the current LPG production in WA is not enough to replace gasoline. Like Australia, there is a long-term declining trend of LPG production in WA as well. It has been found that overall LPG production in WA has been reduced drastically (i.e., around 53% reduction compared to 2010 levels) and the current production is the lowest ever in the history of WA since 1999 (Department of Mines Industry Regulation and safety, 2018).

$$Liquid\ petroleum\ gas\ requirement\ in\ ML\ per\ year\ to\ replace\ all\ the\ gasoline\ requirement\ in\ WA = (2262 \times 1.2) \quad (4.5)$$

Where,

1 Litre gasoline provides mileage equivalent to 1.2 L of LPG (Hoque et al., 2020a)

The gasoline requirement of WA= 2262 ML/year (Hoque et al., 2020a)

It has also been stated that using CNG and LPG in vehicles is not the most effective way to tackle the energy security and climate change problems (Hoque et al., 2020a; Raslavičius et al., 2014). Moreover, both the natural gas and LPG are versatile forms of energy that could be used for many industrial and commercial purposes other than in vehicles. Cohan and Sengupta (2016), for instance, has investigated that it is better to use natural gas in the power plant to produce electricity rather than using it in a CNG vehicle. They state that CNG vehicles produce more GHG emissions than coal-fired electricity and oil furnaces due to the low-efficiency of IC engines (Cohan and Sengupta, 2016; Hoque et al., 2020a).

4.5.2 Summary

It is concluded that further uptake of gas vehicles to replace gasoline in WA seems uncertain. Below is a summary of the aforementioned facts:

- Sixty-nine percent of Australian natural gas is produced in WA. It has been estimated that proved and probable commercial gas reserves of WA are only sufficient to run until 2045.
- The WA is already in long-term contracts with serval companies to export LNG and 97% of the WA's conventional gas reserves are held by the LNG export companies and their joint ventures.
- WA government has introduced a policy to supply only 15% of its natural gas (of equivalent LNG production) to the WA domestic market. Ninety-eight percent (98%) of this gas is used for electricity production, industrial purpose, mining and domestic purpose. The remaining 2 % is used for other commercial purposes. Additional around 84 PJ of natural gas would be required to replace all gasoline in WA. The existing reserves are barely sufficient for the domestic market, and, therefore, there is no gas available for use as a fuel in the transport sector. To save gas for the electricity generation, household and industrial applications seem to be a better option than its use in the transport sector.

- Unlike natural gas, only a small portion of the LPG is produced in WA. In 2017, there were only around 800 ML of LPG produced in WA. It could be estimated that around 2714.4 ML of LPG is required to replace all the gasoline of WA. So, the current LPG production in WA is not enough to replace all the gasoline need for the WA transport sector.

4.6 Biogas

Biogas is produced by anaerobic digestion of organic matters in the absence of oxygen where micro-organisms break down the biodegradable material into gas. Biogas can be used for heating, cooking and electricity generation. There are around 650 TWh of biogas produced in the World. A small amount of biogas (less than 1%), however, is used for transportation. Disperse location of feedstocks (Hoque et al., 2019a), purification of impurities (Nicolas and Steve, 2009) and requirement of methane improvement in biogas (Parliament of Australia, 2018) are the major barriers to its use in automobiles. Impurities, such as hydrogen sulphide (H_2S), ammonia (NH_3), water vapour, siloxane, dust and dirt often remains with biogas. H_2S, for example, is a highly corrosive gas that is harmful to the engine cylinder liner and other parts. Biogas contains 35%-65% methane. To be used in a vehicle, the percentage of the methane in biogas should be more than 90% that could be achieved by removing CO_2 from biogas, but this additional step adds more cost. This section discusses the opportunities of biogas as a transportation fuel in WA.

4.6.1 Potential of biogas as an alternative fuel for gasoline vehicles in WA

Energy recovery from waste is relatively low in Australia compared to other countries in the World. Around 64 million tonnes of waste are generated in Australia and only 2.3 million tonnes are used for energy recovery (Pickin and Randell, 2017). Biogas production in Australia is also quite small. Around 19.1 PJ of the total energy has been produced from biogas in Australia (Farrell, 2017). There are a number of small biogas facilities in the east coast of Australia (Harris, 2017). Animal manures, fruit and vegetable wastes are used as feedstocks in those plants. Due to the dispersed location of feedstocks, electricity is produced from small-scale plants and transferred to the grid (Brooksbank et al., 2014). Understanding the appropriate conversion technologies, matching proper technology types with different wastes, fuel preparation and handling, disperse location of feedstocks, low/moderate landfill levies are found to be the major challenges for biogas and bioenergy production in Australia (AECOM Australia, 2016; Harris, 2017; Pickin and Randell, 2017).

Like Australia, energy recovery from waste is also quite low in WA due to it disperse population centres. It has been found that only 0.035% of the waste is converted to energy in WA (Pickin and Randell, 2017). WA's two biogas plants, located in Shenton Park and Jandakot, use organic wastes from household, hotels and markets to produce electricity for the grid (Brooksbank et al., 2014). Around 126.9 GWh of electricity is being produced by using biogas in WA, which is about 0.34% of the total electricity production in WA (Hoque et al., 2019a). Municipal waste, different animal manures and sewage sludges are the three potential feedstock for biogas production in WA (Brooksbank et al., 2014; Hoque et al., 2019a, 2020a):

- The large distances among collection points, minimum recovery infrastructures and moderate landfill levy (60 AUD/ton) are the major barriers to energy recovery from municipal wastes in WA (Pickin and Randell, 2017). Besides, there is also a lack of waste-specific energy recovery facilities for various types of waste.
- Any farm with more than 1000 cows or 500 sows or 5000 pigs could be viable for biogas production. In the southwest part of WA, there are approximately 16 diaries with 1000 or more cows, and 16 piggeries with 5000 pigs (Brooksbank et al., 2014). So, there could be a number of potential biogas projects in those regions in WA. This needs further assessment as the financial viability would reduce if the animals spend more time in grazing. Besides, it is quite difficult to use the biogas as a fuel from these scattered farms (Hoque et al., 2020a).
- Similarly, biogas production from sewage treatment facilities would only be feasible if a large scale centralized sewage treatment facility is built. This is not feasible in WA due to its low population density and dispersed locations (Brooksbank et al., 2014; Hoque et al., 2020a).

As discussed earlier, the use of natural gas as a transport fuel is also not feasible in WA (Hoque et al., 2020a) because there is lack of gas infrastructures (refuelling and piping network) in WA and there are dispersed population centres with large distances. Due to these reasons, in situ electricity production from biogas seems more feasible from these disperse sources (Hoque et al., 2019a, 2020a).

4.6.2 Summary

Energy recovery from waste is quite low (0.035%) in WA. Sewage sludge, animal manure and municipal waste are the three potential feedstocks for biogas in WA. As these feedstocks are located in a dispersed manner in WA, it would require long-distance transport to carry these feedstocks to chemical plants for biogas production. Electricity production by using biogas seems more feasible from these scattered sources.

4.7 Hydrogen

Researchers believe that hydrogen is the future fuel as it is abundant in amount in the earth atmosphere (Nikolaidis and Poullikkas, 2017). During the combustion of hydrogen, only water is produced as an emission, which is non-toxic (Hoque et al., 2020b). One kilogram of hydrogen can carry 2.4 times the energy of natural gas, but its storage, refuelling and transportation are still a problem due to its low energy density by volume (Hydrogen Strategy Group, 2018). This section describes the opportunities of hydrogen as a transport fuel in Western Australia.

4.7.1 Potential of hydrogen as a transport fuel in WA

Hydrogen can be produced from several renewable and non-renewable sources, such as fossil fuel (e.g., natural gas, heavy oil etc.), electricity (both renewable and non-renewable) and biomass (Nikolaidis and Poullikkas, 2017). Among the fossil-based processes, hydrocarbon reforming is the most used method due to its simplicity and cost-effectiveness (Nikolaidis and Poullikkas, 2017). The method using natural gas as a feedstock is utilized for the majority of the hydrogen production in the USA (US Department of Energy, 2018). Water splitting, as a hydrogen production process, on the other hand, is gaining its interest as this process could be accomplished by the use of both renewable and non-renewable electricity (Hydrogen Strategy Group, 2018; Nikolaidis and Poullikkas, 2017). It has been stated that hydrogen production in Australia could bring a new economic opportunity as Japan, South Korea and some other countries like Norway, Saudi Arabia, and Brunei show increased demand for clean hydrogen. Australia, in this regard, poses some advantage due to its renewable energy resources, especially wind and solar (Hydrogen Strategy Group, 2018). The activities related to hydrogen production in Australia are summarized as follows (Hydrogen Strategy Group, 2018):

- The Australian Capital Territory (ACT) is planning to set up a 1.25 MW electrolyzer to produce hydrogen from renewable electricity.
- The Queensland government is planning to conduct a feasibility study to produce hydrogen using solar energy. The project would also test the viability to export hydrogen to Japan.

- The South Australian government published a study related to hydrogen road map for the state in September 2017. Various initiatives regarding hydrogen implementation are under way since then. For example, the government has announced intention to fund a 10 MW hydrogen fired gas turbine to produce electricity and another 5 MW for hydrogen fuel cells. Hydrogen would be produced by using local wind and solar energy.
- An Australian and Japanese joint project at the Latrobe valley, Victoria, aims to evaluate the viability of exporting hydrogen to Japan.
- Yara Pilbara Fertilizers (YPF) has a pilot demonstration project in WA that would produce hydrogen from solar electrolysis which would then be used for the company's ammonia production.
- ATCO Australia is going to get funding to evaluate the viability of producing hydrogen gas from solar electrolysis.

The Western Australian Government announced a hydrogen strategy in July 2019 emphasising hydrogen production through WA's renewable wind and solar energy potentials (Government of Western Australia, 2019). Excellent wind and solar potential, land availability, skilled workforce and existing industry presence (through LNG production) are considered as advantages to WA compared to other regions. According to the strategy report (Government of Western Australia, 2019):

- The WA government would devise hydrogen regulations and standards.
- The WA government would establish a 10 million AUD fund to support renewable hydrogen production though private sectors.
- Hydrogen refuelling stations for vehicles would be available in WA by 2022.
- Hydrogen would be a significant fuel source for the WA transport sector by 2040. Recently this target has been advanced to 2030 to increase the local jobs in WA to face the economic downtown by COVID-19 (PV magazine, 2020).

Hydrogen production, however, in WA as like the whole Australian scenario is still in the demonstration and pilot study phase. To check the viability of hydrogen as a transport fuel in WA, three fuel cell buses were included in the Transperth bus fleet during the period from 2004 to 2007 (Government of Western Australia, 2008). The trial was successful in terms of its reliability. Regarding the public perception, users were quite supportive and positive towards the clean hydrogen (Government of Western Australia, 2008). Recently, ATCO, a local Australian company, has received AUD 1.5 million funding to test the viability of producing hydrogen from water electrolysis by using solar energy. Besides, Yara Australia has planned to build a hydrogen electrolyser at their Pilbara ammonia plant. The aim of the project is to check the viability of hydrogen as a replacement of natural gas for ammonia production (Hydrogen Strategy Group, 2018).

Western Australia has natural gas as a feedstock to produce hydrogen. However, as mentioned in the natural gas section, WA could survive only for another 27 years with the existing gas reserves, and 97% of the WA's conventional gas reserve is held by the LNG export companies and their joint ventures. There is no sufficient gas in the domestic market in WA to meet the needs of the transport sector (Hoque et al., 2020a). Importantly, one of the reasons for the hydrogen production by WA government is to reduce the usages of natural gas (Government of Western Australia, 2019). Similarly, biomass and biowaste sources cannot be considered for hydrogen production in WA due to their highly dispersed locations (Department of Primary Industries and Regional Development, 2018; Farine et al., 2012; Hoque et al., 2020a) as mentioned in ethanol and biogas sections.

Ally and Pryor (2007) argue that hydrogen can be produced in WA through water electrolysis by using WA grid electricity as there was a significant amount of surplus electricity in the grid especially during the off-peak hours. As mentioned in the electricity section, WA grid is already cleaner compared to other states in Australia with 53% natural gas based and 7% renewable (mainly wind and solar) electricity. Besides, approximately 37% of the electricity in the WA grid is expected to be from renewable energy by 2030 (Hoque et al., 2019a, 2020a; The Climate Institute, 2009). It has also been estimated that all the electricity requirement for hydrogen production plants in WA could be possibly supplied from renewable energy due to the state's enormous amount of wind and solar energy resources (Hoque et al., 2020b; Bruce et al., 2018). Considering these scenarios, hydrogen production through electricity using electrolysis as a process seems to be a potential option for WA (Hoque et al., 2020a; Hydrogen Strategy Group, 2018).

Electrolysis uses water as feedstock that requires around 9 kg of water to produce 1 kg of hydrogen (Hydrogen Strategy Group, 2018). Around 1,484.23 gigalitres of physical water is consumed in WA for different purposes (52% for non-agricultural industries, 25% for agriculture and 3% for household consumption) (Australian Bureau of Statistics, 2017a). One kg of hydrogen is equivalent to 6 litres of gasoline (**Table 4.5**) and total gasoline requirement in WA is around 2,262 million litres. Based on this information, it can be calculated that to replace all the gasoline requirement of WA, 3393 million kg (**Equation 4.6**) water will be required that is only 0.22% of all physical water requirement for WA. This water for hydrogen production in the WA can be sourced from renewable based desalination plants as around 50% of WA water is sourced from such plants (Hoque et al., 2019a, 2020a).

Table 4.5: Energy and driving distance equivalences of hydrogen compared to gasoline

Basis	Energy content and mileage	Equivalence
Energy content	Energy value of 1 kg hydrogen ≈120 MJ (Hydrogen Strategy Group, 2018) Energy value of 1 L gasoline ≈ 30 MJ (Hydrogen Strategy Group, 2018)	1 kg of hydrogen ≈ 4 litre of gasoline
Driving distance	According to Toyota Mirai: 0.01 kg of hydrogen provides 1 km of mileage (Hoque et al., 2019a) According to Toyota Corolla: 0.06 L gasoline provides 1 km of mileage (Toyota Motor Corporation, 2019)	1 kg of hydrogen ≈ 6 litre of gasoline (This estimation can be varied for different vehicle due to the fuel consumption per km)

$$Water\ requirment\ for\ electrolysis\ to\ produce\ hydrogen\ to\ replace\ all\ the\ gasoline\ of\ requirment\ of\ WA\ with\ hydorgen\ in\ Million\ kg\ = (2262 \div 6) \times 9 \tag{4.6}$$

Where,

Water requirement to produce 1 kg hydrogen = 9 kg (Hydrogen Strategy Group, 2018)

Gasoline requirement of WA= 2262 ML (Hoque et al., 2019a)

1 kg of hydrogen = 6 litres of gasoline according to the driving distance (Source: Table 4.5)

By looking at the WA government policy and strategies, hydrogen fuel cell vehicles could be a potential option in future as the WA government is planning to support the hydrogen infrastructure, such as production, distribution and refuelling (Government of Western Australia, 2019; Hoque et al., 2020a, b). Based on the resources availability aspects as discussed above, hydrogen can be produced through water electrolysis. So, triple bottom line assessment of hydrogen as a transport fuel for the replacement of gasoline should also be conducted as the state’s vehicle types are passenger vehicle dominant.

4.7.2 Summary

The following is the summary of the facts discussed above:

- It has been stated that the hydrogen production in Australia could bring a new economic window as several countries have demand for clean hydrogen.
- According to the policy of the WA government, hydrogen would be one of the significant transport fuels in the state by 2030. The state government is planning to support hydrogen infrastructure, such as production, distribution and refuelling stations.
- Due to the surplus electricity in the WA grid and renewable wind and solar potential, hydorgen can be produced through water electrolysis in the state.
- It has been found that 9 kg of water is required to produce 1 kg of hydrogen. In total, 1,415 gigalitres of physical water is consumed in WA for different purposes. It is estimated that only 0.22% of all physical water requirement of WA would be required to produce hydrogen that could replace all the gasoline requirement for WA.
- This warrants that the viability of the passenger vehicle with hydrogen as a fuel for the replacement of gasoline should also be conducted as the state's vehicle types are passenger vehicle dominant.

4.8 Conclusions

The WA transport sector is still heavily dependent on imported fossil fuel. The people of WA rely on passenger vehicles as the public transport is not popular in the state due to low population density and large distances between population centres. It has been found that more than 78% of the total vehicles in WA are passenger vehicles, and 87% of those depend on gasoline. This over dependence on imported fossil fuel not only increases the environmental pollution but also puts the state at a risk of fuel security. It is an urgent need for the state to adopt suitable alternatives to gasoline. Possible alternative fuel options for gasoline passenger vehicles are discussed in this chapter based on the long-term availability of the locally available feedstocks. Based on the availability of the resources in WA as summarized in **Table 4.6,** E65 (65% ethanol and 35% gasoline) from wheat, straw and mallee wood, electricity for battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEVs), and hydrogen fuel (produced by water electrolysis) are considered in this study.

Table 4.6: Summary of the selected fuels

Fuels	Reasons for selection
Ethanol (E65)	• There are three potential resources in WA such as cereal straw, wheat and mallee to ensure long term supply of feedstocks for ethanol production. These feedstocks are estimated to supply ethanol blend E65 for WA. • Cereal straw is an unused by-product of grains in WA while mallee is an inedible source of feedstock. Besides only a small portion of ethanol (E 10) is considered from wheat without affecting the food supply chain.
Electricity (for EV and PHEV)	• The current electricity grid in WA has a significant amount of surplus which can accommodate around 10% (around 200,000) of total WA vehicles. • Current electricity generation mix of WA is comparatively cleaner than other states of WA. • Estimation suggests that all the electricity requirement of the state could be sourced by renewable energy. It has been forecasted that there will be around 37% of renewable energy in WA grid by 2030. • Due to having large parking spaces, electric vehicles can be charged overnight at home, offices and shopping centres in WA. • To support the electric vehicles, a subsidized home charging electricity plan during off-peak hours for BEV and PHEV is already available in WA.
Hydrogen	• Hydrogen could be produced in WA utilizing its access electricity from the current electricity grid especially during off-peak hours. • Due to the availability of wind and solar utilities in WA, all the electricity requirement for the hydrogen production plant could be possible to supply from renewable energy. • To produce hydrogen through electricity, water is required as a feedstock. Only 0.22% of state's total physical water consumption, however, would be sufficient to supply hydrogen equivalent to total gasoline requirement of WA. This water can easily be sourced through the renewable based water desalination plants as 50% current WA water is produced through such plants. • WA already has the skilled workforce to handle the pressurised gas through its LNG export companies. • According to the WA government hydrogen strategy plan, the hydrogen will be one of the significant fuels in WA by 2030. Besides, there would be hydrogen refuelling stations for vehicles in WA by 2022.

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Chapter 5

Implementation of Framework: Environmental Assessment

Abstract

Alternative fuels for the transport sector are being emphasized due to energy security and environmental issues. Possible alternative fuel options need to be assessed to realize their potential to alleviate environmental burdens before policy formulations. Western Australia (WA) is dominated by private cars, accounting for around 72% of vehicles with 87% of those using imported gasoline and resulting in approximately 14% of greenhouse gas (GHG) emissions from the transport sector. There is an urgent need for WA to consider alternative transport fuels not only to reduce the environmental burden but also to avoid future energy security consequences. This study assesses the environmental life cycle assessment (ELCA) of transport fuel options suitable for WA. The study revealed that ethanol (E65), battery electric (BEV) and plug-in electric vehicle (PHEV) options can decrease global warming potential (GWP) by 41%, 29% and 14%, respectively, when compared to gasoline. The BEV and PHEV also showed better performance than gasoline in the fossil fuel depletion (FFD) and water consumption (WC) impact categories. Gasoline, however, demonstrated better environmental performance in all the impact categories compared to hydrogen and that was mainly due to the high electricity requirement during the production of hydrogen. The findings of the study would aid the energy planners and decision makers in carrying out a comparative environmental assessment of the locally sourced alternative fuels for WA.

5.1 Introduction

Rising population coupled with intensive industrialization is increasing the demand for conventional fuels, which in turn results in the increase of exploitation of scarce natural resources and environmental degradation. As a consequence, increasing consumption of natural resources and intensifying environmental impacts are becoming more serious concerns globally (Xing et al., 2016). Fossil fuels comprise around 80% of the global primary energy consumption, 58% of which is consumed by the transport sector alone (Moghaddam et al., 2015). According to the United States Environmental Protection Agency (US EPA), 95% of transportation energy originates from fossil fuel that causes 14% of total greenhouse gases

(GHG) (UNEP, 2017). Due to the over-dependence of fossil fuels, there is an immediate need to look out for alternative transport fuel to achieve greater sustainability (Brondani et al., 2015).

Traditionally, fossil fuels have dominated the Western Australian energy supply. The consumption of energy in WA is also growing at around 5% per annum (Western Australian Planning Commission, 2014). During 2016–2017, 1179.5 PJ of energy was consumed in WA. Among the total energy consumption in WA, 97% is currently sourced from fossil fuels (coal, oil and natural gas) (Department of the Environment and Energy, 2017). WA's transport sector alone consumed 251PJ of energy (19%) which is the second largest energy consumption sector after mining that consumes around 23% (Department of Industry Innovation and Science Australia, 2016). Almost 100% of WA's transport fuel originates from non-renewable fossil sources (Australian Bureau of Statistics, 2017b). The state government is, however, committed to meet a significant portion of energy demand from renewable energy (RE) to achieve Australian's GHG emission reduction target of 26–28% by 2030. The only viable way to achieve this target is to explore various sources of alternative fuels for the transport sector (Department of Finance Public Utilities Office, 2012).

WA is one of the private car dominated states in Australia, where public transport is not very popular due to disperse locations and distances between population centers (Biswas et al., 2013b). Around 78% of vehicles in WA are passenger cars, and 87% of these vehicles use imported unleaded gasoline (Australian Bureau of Statistics, 2017c). With petrol as the dominant transport fuel, around 14% of GHG emissions are emitted from the transport sector of WA (Biswas et al., 2013b). Heavy reliance on imported fossil fuel can also challenge the state's energy scarcity issue, as the fluctuation of price and geopolitical conflicts impacting fossil fuel supply were observed over recent decades (Blackburn, 2014; Department of Resources Energy and Tourism, 2011).

Considering the current situation of WA, it appears that the private passenger car dominant transport sector may suffer from energy security issues and associated environmental complications, such as global warming impact and urban air pollution. Therefore, there is an urgent need for WA to consider suitable alternatives to gasoline as the proportion of gasoline passenger vehicles is quite high (72%) in the state (Australian Bureau of Statistics, 2017c). It is essential to assess the life cycle environmental impact of any alternative fuel as their use may produce less tailpipe emissions but could cause higher emissions during the production of these fuels (Biswas et al., 2011; Biswas et al., 2013b). A life cycle assessment (LCA) approach, which follows ISO 14040-44 and considers all stages of the product life cycle needs to be conducted to determine the environmental impacts of alternative fuels (Hoque et al., 2019).

A comprehensive literature review in Chapter 2 prior to this study based on seventy seven (77) LCA articles of alternative fuels suggests that although LCA is a well-established method for environmental assessment, there is still a need for region specific analysis as the generalized results and recommendations for one region may not be replicated in other regions due to regional variations (Hoque et al., 2020b). For example, GHG emissions for a hybrid vehicle varied by more than 100% in different Canadian cities mainly due to the variation in electricity mix (Requia et al., 2017). Sources of various feedstocks (or distance travelled) and their long-term availability to produce alternative fuels are crucial for the economic and environmental feasibility of alternative fuel for any region (Balat and Balat, 2009; Farine et al., 2012; Hoque et al., 2019). The selection of proper indicators is also deemed necessary for a particular region for assessing a reliable sustainability strategy (Hoque et al., 2019; Hoque et al., 2020b; Lim and Biswas, 2015; Lim and Biswas, 2017). Besides, most of the studies in the literature (more than 75%) only considered fuel production and/or the use phase of fuel (Hoque et al., 2020b). Life cycle assessment of transport fuels, however, remain incomprehensive if associated changes in vehicles due to the use of alternative fuel is not considered within the system boundary (Hoque et al., 2020b). Thus, this chapter examines the environmental component of the framework (chapter 3) according to the existing research gaps in the literature. The framework is implemented locally in passenger vehicle dominated transport sector of WA, as mentioned in chapter 4.

In Western Australia, some environmental life cycle assessment (ELCA) studies (Biswas et al., 2013a; Biswas et al., 2013b) have also been conducted to assess hydrogen and electricity as an alternative to gasoline in 2013. The current study, however, investigates further by considering all the possible alternative fuel options based on the availability of feedstocks in WA. Secondly, any modifications and arrangements in terms of material and process changes to make vehicles suitable for alternative fuel use are also incorporated within the system boundary to precisely calculate the environmental performance of these fuels. Thirdly, identification and selection of indicators; and fuel selection based on resource availability and geographical conditions for WA are integrated with ELCA for greater sustainability. The study considers a streamlined environmental life cycle assessment of the selected fuel options; and compares the environmental impacts of alternative fuels. Uncertainty analyses have been carried out to establish the applicability and validity of the results. The findings of the study would be beneficial for the policymakers in WA for formulating environmental protection policies and strategies.

5.2 Methodology

This study aims at the environmental life cycle assessment of alternative transport fuel options for Western Australia. The environmental performance of the selected fuels has been assessed and compared with conventional gasoline. The first step of the methodology is to select alternative fuels based on the locally available resources followed by indicator selection, environmental life cycle assessment and finally the interpretation of the results based on per vehicle kilometre travelled (VKT). Four alternative options such as ethanol-gasoline blend E65, electricity for BEV and PHEV and hydrogen were selected for the study as an alternative of gasoline due to the domination of gasoline passenger vehicle in Western Australia. As described in chapter 4, E65 was based on three available feedstocks in WA such as cereal straw, wheat and mallee wood. Detail discussion regarding fuel selection is removed from this chapter so as to avoid repetition with chapter 4.

5.2.1 Indicator development for ELCA

Indicators need to be selected for a particular region (Hoque et al., 2019; Hoque et al., 2020b; Lim and Biswas, 2015; Zanchi et al., 2018). For this current study, initially, five indicators such as global warming potential (GWP), fossil fuel depletion (FFD), eutrophication, water consumption (WC) and land use were selected by reviewing the local and international literature. An expert survey was then conducted to determine the relevance of the preselected indicators for the Western Australian transport sector (Lim and Biswas, 2015; Lim and Biswas, 2017). The respondents have been classified under academia, government and industry categories. Questionnaires were sent out to experts to conduct the survey after obtaining the necessary ethics approval from Curtin University, Australia (**Appendix-C**). Indicators that were considered important by more than 50% of the experts (i.e., where the total number of survey respondents are 30) were selected for the study. Four indicators namely GWP, FFD, WC and land use were then selected based on the expert opinion. Eutrophication was considered less important for this study by 57% of respondents. Eutrophication may occur in the terrestrial and aquatic environment but later can cause problems in Australia due to the nutrient runoff from the agriculture and conversion stages of alternative fuels. Respondents commented that alternative fuels in WA could be produced in a confined space and feedstocks for the current study might also produce quite a minimal effect on freshwater.

The new indicators proposed by the experts were also investigated to justify their relevance in this current study**.** The reasons for inclusion and exclusion of selected and proposed indicators by experts are described in **Table 5.1**. Some of the proposed indicators were not included as they were either non-existent or weak for the Western Australian alternative fuel assessment. For example, the human toxicity indicator was not considered for this study in WA due to its low population density (1 people/km^2), geographical specificity (such as the location of WA cities near the sea), and wind speed. Because of this, in Australian cities, the possibility of human exposure to toxic substances was 160 times lower than for Western Europe (Renouf et al., 2015). Human exposure factors related to toxicity was also 20 times lower in Australia than in Western Europe due to these aforementioned reasons (Renouf et al., 2015). Besides, biodiversity was suggested but it was ignored because the alternative fuel options for the current study and their feedstocks (such as straw and mallee and a small portion of wheat for ethanol) are based on existing land and agricultural practices which were not developed through new land/forest clearing (Renouf et al., 2015).

Table 5.1: Justifications for included/excluded indicators.

Indicators	Justifications
GWP ($kgCO_2$/VKT)	*Eighty-seven percent (87%) of the respondents considered global warming potential (GWP) as an important indicator for the current study in WA during the survey process.* Different life cycle phases of alternative fuels such as feedstock production, conversion from feedstocks to fuel and transportation are GHG emissions intensive (Hoque et al., 2020b). Around 14% of GHG emission is from the transport sectors of WA (Biswas et al., 2013b). The government of WA is committed to reducing the significant portion of GHG emission from transport sectors through alternative fuels by the year 2031 (Department of Finance Public Utilities Office, 2012).
FFD (MJ/VKT)	*Sixty-seven percent (67%) of the respondents considered fossil fuel depletion (FFD) as an important indicator.* Almost all the life cycle stages of alternative fuels consume fossil fuel (such as chemicals and fertilizers during the agricultural production of feedstock; transportation of feedstocks; and energy requirements during the conversion stage) (Hoque et al., 2020b). The transport sector alone consumed 251 PJ of energy (19%) which is the 2nd most energy consumable sector in WA (Bureau of Meteorology, 2016).
WC*	*Sixty-three percent (63%) of the respondents considered water consumption (WC) as an important indicator.* Agriculture production of feedstock and conversion of alternative fuels requires water as a raw material. Electricity and other fossil fuel requirements in the different stages also have

(cm^3 of water/VKT)	their own water use impacts (Australian Bureau of Statistics, 2017a). Almost all of WA (around 85%) falls under the semiarid or arid climate by nature (Rangelands NRM, 2018). Estimations suggest that there could be a possible water crisis in the near future in WA as the water supply is reducing over time from both ground and surface water sources (McFarlane, 2016; Taylor, 2015; Water Corporation, 2018).
Land use (cm^2.a/VKT)	*Fifty-three percent (53%) of the respondents considered it as an important indicator.* When any feedstock for alternative fuel derived from agriculture may produce higher land use impact than the fossil fuel (Grant et al., 2016). Though the WA state has a huge land area (around 2.5 million km^2), additional stress on land for biofuel can produce an impact on food production (Edge Environment and Life Cycle Strategies, 2016).
Eutrophication (kg of PO_4 eq /VKT)	*Eutrophication was selected initially through review but 57% of the respondents considered it as a less important indicator for the current study.* Eutrophication was identified by the experts as a less important indicator for WA conditions mainly for two reasons. On the production side, as eutrophication results from the direct discharge of effluent to water, it may not be an issue since the alternative fuels are produced in confined spaces and the energy plant wastes are landfilled. Secondly, the alternative fuels are assumed in this study to be sourced from existing agricultural by-products (wheat straw in this study) or, in the case of mallee, may potentially reduce the nutrient runoff (Stucley et al., 2012).
Human toxicity (Toxic unit for human, CTUh/km)	*Two respondents from academic and industry categories emphasized the importance of 'human toxicity' due to its importance on human health.* The toxicity indicators are found to be either weak or nonexistent in Australian biofuel and bioenergy projects though upstream agriculture production of feedstock may release a small amount of toxic pesticides but other stages of fuel production are not directly related to emissions (heavy metals, pesticides, hormones, and organic chemical) which cause toxicity (Australian Renewable Energy Agency, 2016; Edge Environment and Life Cycle Strategies, 2016). It has been found that due to the low population density (one people/km^2 in WA) and geographical specificity (most of the Australian cities are near the sea), toxicity substances emitted to the soil in Australia has 160 times lower possibility for human exposure than Western Europe (Renouf et al., 2015). The human exposure factor was also found to be 20 times lower for toxic substances emitted to the air and water (Renouf et al., 2015).
Biodiversity (Species loss per m^2/km)	*Two respondents from academic and industry categories had suggested 'biodiversity' as land clearing due to the agriculture production of biofuel can destroy the ecosystem and biodiversity.* Most of the lands in Australia were cleared more than 20 years ago and any new land clearing in the country is under strict policy from the Australian government regarding nature conservation and protected areas (Grant et al., 2016; URS Australia, 2008). Biodiversity is considered important where activities from the life cycle of a fuel disturb the local animals and plant life (Renouf et al., 2015). Feedstocks for alternative fuel production for the present

	study such as straw (by-product from current agriculture) and Mallee (grown within the narrow belt of existing agricultural systems) and a small portion of wheat for ethanol (from existing agriculture); electricity for EV; and sea water for hydrogen have no direct relationship with the land/forest clearing which can affect biodiversity or ecosystems.
Vehicle exhaust emissions (kg/km)	*Three respondents from the academic category proposed 'vehicle exhaust emission' as air quality is the important driver for the application of alternative fuel.* In WA, the contribution of atmospheric air pollution from vehicles was quite low compared to mining and industrial applications. However, direct exposure from low elevated vehicle exhaust emissions (such as CO, PM and NO_x) have the potential to cause significant human health problems (Renouf et al., 2015). Due to this reason, these emissions are considered as social sustainability indicators under the public health category for the current study and were not included here in the environmental life cycle assessment (ELCA) to avoid repetition. Besides, tailpipe CO_2 emissions are already included under the GWP impact.
PM formation (kg/km)	*Two respondents from academic and government categories shared their view regarding 'PM formation' due to its potential damage for human health.* PM emission all over Australia is not the general problem due to the location of its main cities near the sea, its wind speed, flat terrain, mild industrialization and lower population densities (Renouf et al., 2015). The country is also ranked 2nd in the world according to the air quality index (Australian Institute of Health and Welfare, 2017). However, PM as a measure of human health is considered a social indicator under the current project due to the aforementioned reasons in the vehicle exhaust emission indicator.
Comparison with traditional fuel per km	*Two respondents from industry and government categories advised to include this comparison as singling out alternative fuels for a life cycle assessment without ensuring traditional fuels are being subject to the same life cycle assessment is not reasonable and would work against alternative fuel uptake.* By following the strategy, gasoline as the baseline fuel was compared with alternative fuel options, as gasoline is the predominant fuel for WA transport sectors.
Direct displacement of food due to ethanol feedstocks (amount of food /km)	*One participant from the government category highlighted the importance of food displacement as biofuel feedstocks may disturb the food cycle.* As described in detail in the fuel selection chapter, feedstocks for the current study (such as straw and mallee and a small portion of wheat) may not disturb the food supply chain in WA. Especially, straw and mallee as they are sourced from the unused resources in WA which have no direct relation with food displacement.

*Amount of water which is taken from the environment during the different activities of the product life cycle.
Any rainfall during the agriculture of feedstock and water from the sea is not included.

Some of the suggested environmental indicators were already considered as social indicators (such as vehicle exhaust emissions as a measure of human health), while some were actually not indicators (such as comparison with fossil fuel and suggestions regarding the consideration of vehicle use phase).

5.2.2 Goal and scope definition

Life cycle assessment for this study follows the ISO 14040 and ISO 14044 (ISO14040, 2006; ISO14044, 2006) framework that starts with the goal and scope definition, followed by boundary selection, life cycle inventory analysis, life cycle impact assessment and interpretation of results. The main aim of the study is to evaluate the environmental performance of various alternative fuel options. This study compares the results with gasoline in order to determine the environmental benefits. The functional unit (FU) for this study is VKT (vehicle kilometre travelled) which allows for comparison between the alternative fuel options. The study considers the ‘well to wheel’ approach to incorporate all the stages of fuel life cycle from resources extraction to its use in the vehicle. Besides, additional vehicle materials (AVM) or arrangements required for vehicles using alternative fuels (such as battery, electric powertrain, electronic components, charger etc. for EV) are included. The mass of the glider was assumed to be the same for vehicles using alternative fuels for fair comparisons (Biswas et al., 2013a; Miotti et al., 2017; Notter et al., 2010; Sharma et al., 2013). The end of life stages was excluded in this study as the study focuses only on the fuel life cycle. The emissions during the maintenance activities associated with the use of alternative fuel in vehicle were not considered as it generates a tiny fraction (around 1%–2%) of emissions compared to the total life cycle of a fuel and vehicle (Sharma et al., 2013; Stasinopoulos, 2016).

5.2.3 Life cycle inventory analysis

Life cycle inventory is the collection of data inputs required for each fuel for the assessment, which was calculated based on the functional unit (VKT).

Gasoline

A consistent reduction trend of ‘crude oil’ quantity reaching Australia was observed in recent years not only due to the closure of refineries in the country but also due to the reduction of refining in the existing refineries (Grant et al., 2016). The crude oil is imported to Australia primarily from UAE (18%), Malaysia (26%) and Indonesia (10%) (Grant et al., 2016; Mushalik, 2017). Besides, the Australian gasoline supply chain shows that it is imported in the refined form to Australia mainly from South Korea (around 45%), Singapore (around 34%) and Japan (around 3%) (Mushalik, 2017). Most of these oil exporting countries source their crude oil from the Middle East. The exact locations of these countries (Mushalik, 2017) helped ascertain the transportation distance. The source of the distances used in this study is the online calculator provided by sea-distances.org (https://sea-distances.org/). The mileage of the vehicle during the usage stage for the alternative fuels was based on the latest survey by the Australian Bureau of Statistics, showing that an average passenger vehicle travels 11,000 km per year in Western Australia (Australian Bureau of Statistics, 2018a) and the average age of the passenger vehicle in the state was 10.23 years (Australian Bureau of Statistics, 2018b). Based on this data, the life of the passenger vehicle has been estimated as 112,567 km for the current study.

Table 5.2: Summary of inventory for gasoline vehicle (GV), electric vehicle (BEV), plug-in hybrid electric vehicle (PHEV) and hydrogen fuel cell vehicle (HFCV) (functional unit, FU= VKT)*.

Parameter	Unit	GV	BEV	PHEV	HFCV	E65
Hydrogen tank	kg	-	-	-	7.77×10^{-4}	-
Battery	kg	-	3.37×10^{-3}	1.07×10^{-3}	2.03×10^{-4}	-
Fuel cell with assembly	kg	-	-	-	9.50×10^{-4}	-
Motor	kg	-	6.11×10^{-4}	4.82×10^{-4}	6.27×10^{-4}	-
Inverter	kg	-	1.03×10^{-4}	7.09×10^{-5}	1.05×10^{-4}	-
Converter	kg	-	2.20×10^{-4}	1.52×10^{-4}	2.26×10^{-4}	-
Motor controller	kg	-	7.82×10^{-5}	5.40×10^{-5}	8.03×10^{-5}	-
Transmission differential and others (cables, cooling unit etc.)	kg	7.55×10^{-4}	5.51×10^{-4}	6.98×10^{-4}	6.65×10^{-4}	7.55×10^{-4}
charger	kg	-	6.37×10^{-5}	3.50×10^{-5}	-	-
Internal combustion engine	kg	1.31×10^{-3}	-	9.14×10^{-4}	-	1.41×10^{-3}
Fuel system	kg	1.60×10^{-4}	-	1.38×10^{-4}	-	1.62×10^{-4}
Exhaust system	kg	2.13×10^{-4}	-	1.83×10^{-4}	-	2.13×10^{-4}

*All the values are calculated for the selected vehicles for this from different sources as mentioned within the text.

The Toyota Corolla was chosen as the proposed vehicle for the usage of these alternative fuels as it is a widely used passenger vehicle in Australia (Australian Bureau of Statistics, 2018b;

Motoring Australia, 2019). Fuel consumption values of the latest Toyota Corolla model are reported to be 0.06 L/km (Commonwealth of Australia, 2019; Toyota Motor Corporation, 2019b). The mass of different parts of the Corolla that were incorporated into the existing design were based on the total curb weight (car weight with standard equipment excluding passenger and any other additional items), estimated from Stasinopoulos et al. (Stasinopoulos, 2016) and detailed inventory for different parts has been readjusted for the Corolla from Notter et al. (Notter et al., 2010). **Table 5.2** shows a summary of the inventory for gasoline and other vehicle materials for the current study. The Japanese electricity grid (Japan Electric Power corporation Center, 2019) was used for all the vehicle component production for fair comparison as the base vehicle was imported to Australia from Japan (Stasinopoulos, 2016).

<u>Ethanol</u>

Three feedstocks such as wheat, straw, and mallee have been considered as the source of E65 for WA. **Figure 5.1** shows the supply chain scenario of ethanol considered for this study. Data related to farm inputs of wheat production were collected from Northam, located in the central wheat belt of WA (Biswas et al., 2008; Engelbrecht, 2015). The average yield of wheat in WA is 1.8 tonne/ha (Wilkinson, 2018b). So, a farm with an average yield of 1.9 tonne/ha was selected for estimating life cycle inventory (LCI) inputs for wheat-based ethanol production.

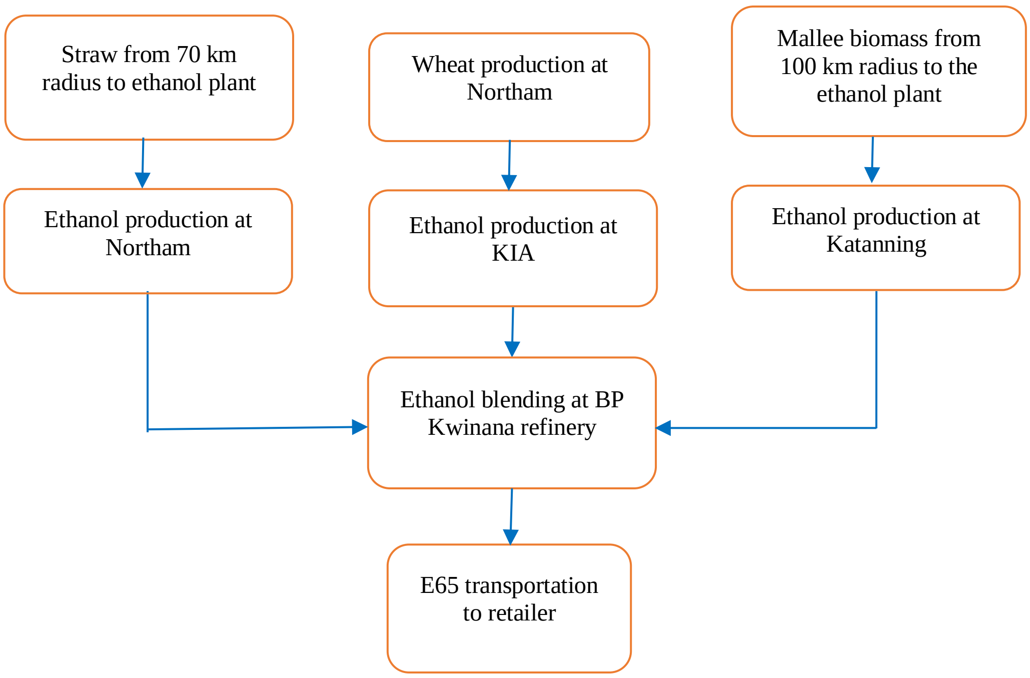


Figure 5.1: The ethanol (E65) supply chain

The transport distances of all chemicals were obtained from the respective organizations. The location of the ethanol (E65) plant was considered to be in the Kwinana Industrial Area (KIA) adjacent to the BP oil refinery. Site for ethanol production from wheat is selected near BP oil refinery due to the following reasons (Williams, 2016 and CBH Group, 2021):

- Almost all the fuels that come to WA are from BP fuel distribution center where required facilities (such as testing, storage, regulatory requirements etc.) are already established.
- All the required chemicals and utilities, including natural gas, are readily available at Kwinana industrial area.
- Wheat can be easily transported to the plant through its already established supply chain as WA's one of the major grain export terminals is located at Kwinana.

N_2O emission from soil is one of the major contributors to GHG emission during agricultural production of feedstocks (Biswas et al., 2008). The field measurement of N_2O emission factor from N fertilizer in WA was found to be as low as 0.1% compared to the IPCC (Intergovernmental Panel on Climate Change) default value of 1% (Engelbrecht, 2015; National Greenhouse Gas Inventory Committee, 2007). **Table 5.3** provides a summary of direct and indirect emission factors used for N_2O and CO_2 from the field. Besides, the conversion factors for C to CO_2 and N to N_2O were used as 3.667 and 1.57, respectively (De Klein et al., 2006).

Table 5.3: Emission factors used for soil emission

Activities	Emission factor	Corresponding Reference
Direct N_2O emission from N fertilizer	0.1%	Biswas et al. (Biswas et al., 2008)
Fraction C in Urea for Urea hydrolysis	0.2	Klein et al. (De Klein et al., 2006)
CO_2 emission factor for lime	0.12	Klein et al. (De Klein et al., 2006)
Emission from leaching		
N fraction lost due to leaching	0.3	Klein et al. (De Klein et al., 2006)
N_2O emission due to leaching	0.0075	Klein et al. (De Klein et al., 2006)
NH_3 volatilization		
Fraction of fertilizer N will be emitted as NH_3	10%	Barton et al. (Barton et al., 2014)
Emission factor for N_2O emission	0.08%	Barton et al. (Barton et al., 2014)

Whether leaching is happening or not depends on the ratio of evapotranspiration (Et) to annual precipitation (P). Leaching is considered when Et/P < 0.8 or Et/P > 1 (Brock et al., 2012;

National Greenhouse Gas Inventory Committee, 2007). The last 7 years of data (Et/P) of the location (31.47113° S, 116.52287° E) confirms that leaching is unlikely to happen on site. Farm machinery production data for WA and the associated emissions were collected from Biswas et al. (2008). Economic allocation was considered in this study to allocate environmental burden to the co-products for all fuel options based on the current prices in WA (Grant et al., 2016). As cereal was produced in WA solely for food production purposes, and the current straw mostly remains unused, no environmental burden was attributed to straw production (Grant, 2018). During ethanol conversion, a 79.47% burden was allocated to ethanol compared to 20.53% for dried distiller grain (DDGS). This allocation for ethanol versus DDGS allocation was found to be consistent with the existing literature, such as Grant et al. (2016) and Muñoz et al. (2014).

As described in the fuel selection chapter, a large amount of cereal straw is produced in WA. Wheat comprises around 70% (around 10 million tonnes out of 14 million tonnes) of total cereal production in WA (Wilkinson, 2018a, b). The same farm was considered to supply both wheat and straw. The excess straw that remains after the soil amendment was 1.92 tonnes/ha (Stucley et al., 2012). Due to the use of straw for fuel production, some additional fertilizers may be required for some farms depending upon the soil conditions, and as such, this study considered a moderate replacement amount of 4 kg Di-ammonium phosphate (DAP), 11 kg Urea and 10 kg K_2O fertilizer (**Table 5.4**). For Urea, transport by sea was considered for importing from Qatar (Olivera et al., 2016). Due to the low bulk densities of straw, the location of the ethanol production plant should be near the farm to reduce high transport emissions (Stucley et al., 2012). A 70 km radius was considered for transporting the straw from farms to the plant for all the selected sites as described in chapter 4 (Brooksbank et al., 2014). Ethanol production in remote locations using lignocellulosic feedstocks (such as straw and mallee for this study) is further justified by the fact that the plants do not require utilities like natural gas and a small amount of electricity requirement can also be fulfilled by renewable solar (Zucaro et al., 2018 and Brooksbank et al., 2014). **Figure 5.2** illustrates the process of ethanol production from lignocellulosic feedstocks (Zucaro et al., 2018; Brooksbank et al., 2014; Mu et al 2010 and Wang et al., 2013). The speed of the ethanol plant considered for this study are 19470 kg/hr for straw and 22686 kg/hr Mallee wood (Mu et al., 2010). Enzyme required for ethanol production was also considered to be produced onsite based on the concept of Mu et al. (2010)

Table 5.4: Nutrient replacement due to straw removal.

Fertilizer	Amount which can be required per tonne of straw, kg (Stucley et al., 2012)	Amount considered for this study per tonne of straw, kg
N	2–10	6
P	0.2–1.5	0.8
K	6–16	7

Like straw, the ethanol plant for mallee was considered from the farms around Katanning (Oil Mallee Association Australia, 2019). The mallee farm input for production was gathered from Crossin (Crossin, 2017). The life of the mallee tree was considered as 30 years with an initial harvest at 6 years age followed by 6 harvests at 4-year intervals. Besides, the average harvest of biomass was found to be 16 gmt per harvest per ha (Crossin, 2017). Mallee trees have a high nutrient efficiency and also receive an additional amount of fertilizers from nearby grain fields (Stucley et al., 2012). Hence, a moderate amount of fertilizers (50 kg DAP, 50 kg Urea and 20 kg Muriate of potash per ha) were considered for this study after each harvest of mallee (Wu et al., 2007). Following the harvest, the mallee biomass was considered to be transported to a processing farm that was 100 km away from the plantation site (Crossin, 2017). Since electricity is generated as a co-product with ethanol in the plants using straw and mallee as feedstock, the environmental burdens allocated to ethanol were 91% for both straw and mallee-based ethanol (Grant, 2018). Inventory inputs for E65 production from all three feedstocks is presented in **Table 5.5**.

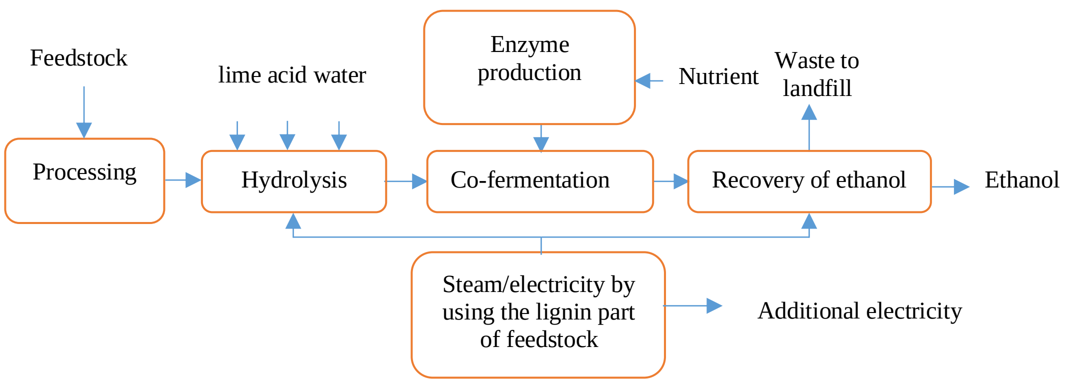


Figure 5.2: Schematic diagram of straw-based ethanol production.

Table 5.5: Summary of inventory for 1 L ethanol production from wheat, straw and mallee after allocation*

		Chemical/Energy	Unit	Wheat	Straw	Mallee
Fuel Production	Agriculture (with required nutrient replacement)	Urea fertilizer	kg	-	3.69×10^{-2}	3.85×10^{-3}
		Di-ammonium phosphate (DAP) fertilizer	kg	10.22×10^{-2}	1.34×10^{-2}	3.85×10^{-3}
		Muriate of potash (MOP) fertilizer	kg	-	-	1.54×10^{-3}
		Flexi-N fertilizer	kg	10.13×10^{-2}	-	
		Potassium chloride as K_2O	kg	-	3.35×10^{-2}	-
		Herbicide & pesticide	kg	2.01×10^{-3}	-	3.06×10^{-5}
		Diesel for farm machinery	L	12.13×10^{-3}	-	1.44×10^{-3}
		Diesel for harvester	L	6.27×10^{-3}	-	7.70×10^{-4}
		Lime application to paddock	kg	10.45×10^{-2}	-	-
		Farm machinery	AUD	7.15×10^{-3}	-	-
		Harvester for mallee	P	-	-	3.89×10^{-4}
		Transportation of chemicals	tkm	4.21×10^{-2}	3.64×10^{-2}	3.99×10^{-2}
	Feedstock transportation to ethanol plant		tkm	2.6×10^{-1}	2.35×10^{-1}	5.27×10^{-1}
	Ethanol conversion	Feedstock	kg	1.99	3.35	5.27
		Water	L	0.25	7.02	4.02
		Enzyme	kg	-	1.88×10^{-2}	1.92×10^{-2}
		Lime	kg	-	8.63×10^{-2}	7.58×10^{-2}
		Sulfuric acid	kg	-	3.79×10^{-2}	1.04×10^{-1}
		Corn steep liquor	kg	-	2.58×10^{-1}	4.08×10^{-2}
		DAP	kg		4.74×10^{-3}	4.8×10^{-3}
		NaOH	kg		1.66×10^{-3}	1.71×10^{-3}
		Heat	MJ	4.05	-	-
		Electricity	kWh	8×10^{-2}	-	-
		Transportation of chemicals	tkm		1.65×10^{-1}	2.17×10^{-1}
Distribution & transportation	Transportation to blending stations		tkm	-	1.03×10^{-1}	1.03×10^{-1}
	E 65 Transportation to retailers		tkm	1.65×10^{-1}		

*DAP: Di-ammonium phosphate, MOP: Muriate of potash; p: process.

Owing to the presence of oxygen in the ethanol molecule and its water absorption, the fuel system component systems are prone to corrosion (Jones, 2007; RAC, 2018a). Therefore, this study considered the use of stainless steel for the fuel tank material such as used for the Holden Commodore (RAC, 2018a). Accordingly, the aluminium components for the injection system and synthetic rubber of the fuel line were replaced with stainless steel and polypropylene respectively (Matějovský et al., 2017). Fuel consumption (0.075 L/km) and tailpipe emission for E65 were based on Jin et al. (2017).

Electricity

The current electricity mix of Western Australia (Table 4.3: fuel selection) was used for charging the electric vehicles. The electric vehicles were considered to be charged overnight during the off-peak period at home as this charging system is already available in Western Australia (Synergy, 2019). The low voltage electricity system caused 2.7% and 5.28% transmission and distribution losses for WA, respectively (PRe'-Consultants, 2016).

To compare with gasoline vehicle (GV), a first-generation Nissan Leaf, with 120–135 km range, was considered as the BEV in previous studies (Miotti et al., 2017; Stasinopoulos, 2016). Vehicle driving range from a single charge, however, is one of the main barriers to the electric vehicle uptake in Australia (Climate Works, 2017). By considering the dispersed locations and large distance between population centres of WA, a new generation Nissan leaf released in 2018 was chosen for this study for comparison. This BEV contains a 40 kWh Li-ion battery pack, and a 110-kW motor (comparable with GV power) to provide a driving range of 270 km (Nissan, 2019; RAC, 2018b). Data for 100 kW BEV materials and powertrain were collected from Miotti et al. (Miotti et al., 2017) and adapted for 110 kW for the current study. This approach was found to be employed by other studies in the literature for consistent comparison among different vehicles (Hawkins et al., 2013; Helmers et al., 2017; Miotti et al., 2017).

A similar plug-in hybrid vehicle, Toyota Prius Prime, was chosen for comparison. Inventory for the BEV and PHEV vehicles is given in Table 5.2. Most of the data for the PHEV were obtained from the manufacturer specifications (Toyota Motor Corporation, 2019a) and, the remaining data were based on available literature (Sharma et al., 2013; US Department of Energy, 2010). According to the Toyota motor corporation, the vehicle comprises a 8.8 kWh (120 kg) Li-ion battery sufficient to provide a 40 km driving range (i.e., 100–134 km/hr) (Toyota Motor Corporation, 2019a). The vehicle uses a dual motor generator (53 kW and 23 kW) drive system. The PHEV also has a 43 litre fuel tank (14% less volume than the gasoline tank) that allows the vehicle run on a pure hybrid mode (0.044 L gasoline/km) (Toyota Motor Corporation, 2019a). The gasoline engine mass of the PHEV was assumed to be 30% less than that of the GV engine (Toyota Motor Corporation, 2019a). The electricity consumption was considered as 155 Wh/km during all-electric mode (US Department of Energy, 2019). Following the methodology of Ciborowski et al. (2007), this study assumes that the vehicle runs on gasoline for 50% of the travel time.

Hydrogen

Hydrogen production through water electrolysis using a proton exchange membrane (PEM) electrolyser was considered due to its higher efficiency and operational pressure (around at 165 bar) compared to the alkaline electrolysis (AE) process (Hinkley et al., 2016). PEM electrolysis uses 54 kWh of electricity to produce 1 kg of hydrogen (Hinkley et al., 2016). **Table 5.6** provides a summary of the life cycle impact for hydrogen fuel production. Electricity requirement for hydrogen compression in different stages was calculated using **Equation 5.1** (Ehsani et al., 2018; Hoque et al., 2020a). The calculated value was verified by comparing it with the data from the study of Australian National Hydrogen Roadmap (Bruce et al., 2018).

$$E_{compression} = \frac{\gamma mRT}{(\gamma-1)W_h}\left[\left(\frac{P}{P_0}\right)^{\frac{(\gamma-1)}{\gamma}} - 1\right] \qquad \textbf{(5.1)}$$

Where, m =mass of hydrogen in kg, γ = ratio of specific heat which is 1.4, P = pressure of hydrogen, P_0 =atmospheric pressure, T = Average room temperature 298 K, W_h = molecular weight of hydrogen (2.016gm/mole), R = Gas constant (8.31 J/mole K).

Desalinated water in WA, was considered for H_2 production. The inventory data for seawater desalination (Table 5.6), was sourced from Shahabi et al. (2015) and Biswas (2009). The study considered solar and wind energy as the sources of electricity for the desalination plants in WA (Shahabi et al., 2015; Water Technology, 2019). Hydrogen distribution through tube tankers using trucks was considered. The transport of 0.3 tonne of hydrogen amounts to approximately 30 tonne freight due to the additional weight of the tubes and accessories (Simsons and Bauer, 2011). The additional weight associated with the tube tankers of this alternative fuel was also considered for accurately estimating the emission. Around 80% of gasoline in WA is consumed in the Perth metropolitan region (BP Kwinana refinery, Personal communication, May 2019). The mean delivery distance of hydrogen was calculated for WA as 138.39 km based on BP locations (Biswas et al., 2013b) and gasoline consumption within and outside the Perth metropolitan region. The delivery distance was considered the same for other fuel options (such as gasoline and E65) from the KIA to retailers.

Table 5.6: Summary of inventory for hydrogen production (FU = per VKT; water desalination inventory for 1 L).

Process		Unit	Amount
Fuel Production	Electricity (Hinkley et al., 2016)	kWh	5.40×10^{-1}
	Desalinated water from sea (Hydrogen Strategy Group, 2018))	L	9.00×10^{-2}
	Hydrogen Compression (Bruce et al., 2018)	kWh	9.42×10^{-3}
Distribution		tkm	1.5×10^{-1}
Water Desalination (1 L) (Shahabi et al., 2015 and Biswas, 2009)	Electricity	kWh	3.00×10^{-3}
	Sodium hypochlorite	g	3.57×10^{-3}
	sulphuric acid	g	6.90×10^{-4}
	sodium metabisulphite	g	7.00×10^{-5}
	Detergent	g	2.72×10^{-3}
	Citric acid	g	9.30×10^{-4}
	Caustic soda	g	4.00×10^{-4}
	Biocide	g	9.86×10^{-3}
	Polypropylene	g	5.00×10^{-5}
	Polyethylene	g	5.00×10^{-4}
	Polyurethane	g	1.40×10^{-4}
	Acrylonitrile butadiene styrene	g	1.27×10^{-3}
	Polyamide	g	1.40×10^{-4}
	Transportation		
	Local (chemicals)	tkm	8.72×10^{-4}
	International (membranes from USA)	tkm	5.48×10^{-4}
	Waste to landfill	tkm	1.10×10^{-2}
Use phase	Hydrogen consumption per km (Toyota Motor Corporation, 2017)	kg	0.01
Vehicle	Vehicle inventories are already in Table 5.2		

In order to compare GV, with HFCV, the same vehicle brand (i.e., Toyota Mirai 2017) that delivers identical power (max 113 kW), was considered. The vehicle comprises a 114-kW fuel cell, a 113-kW motor and a 5 kg hydrogen tank (mass of total tank 87.5 kg) to provide a driving range of around 500 km (Toyota Motor Corporation, 2017). The inventory data for an 80-kW polymer electrolyte fuel cell and powertrain of 100 kW HFCV were collected from Miotti et al. (Miotti et al., 2017) and then customized for both the114-kW fuel cell and 113 kW HFCV for this study. Inventory for the HFCV is summarized in Table 5.2. The vehicle fuel consumption was considered as 0.01 kg/km (Toyota Motor Corporation, 2017).

5.3 Life cycle impact assessment

Life cycle environmental impact assessment was conducted to determine the indicators using Simapro 8.4 software (PRe'-Consultants, 2016). The Australian indicator method was used to determine these indicators including GWP, WC and land use (**Table 5.7**). Besides, the FFD indicator was measured based on the energy content of fuel by using the CML method, which is aligned with the Australian best practice impact assessment guide (Renouf et al., 2015).

Table 5.7: Impact assessment methods to estimate the environmental impacts

Indicators	Impact Assessment Method	Unit
Global warming Potential (GWP)	IPCC GWP 100 based on IPCC 2013 (Church et al., 2013)	$kgCO_{2\text{-}eq}$/VKT
Fossil fuel depletion (FFD)	CML-IA baseline V3.03 / World 2000. Based on lower heating value. Does not include renewable energy and energy from waste.	MJ/VKT
Water Consumption (WC)*	Australian indicator set v2.01	cm^3 H_2O/VKT
Land Use**	Australian indicator set v2.01	cm^2.a/VKT (10^{-8} ha.a/VKT)

*Usually measured in m^3/VKT but cm^3 /VKT is used in this chapter to show better comparison among the fuels

**Usually measured in ha.a/VKT but cm^2.a/VKT is used in this chapter to show better comparison among the fuels

The calculation of ELCA indicators is governed by **Equations 5.2 – 5.5**.

$$GWP/VKT = \sum_{i=1}^{N}(EF_{i\,CO_2} \times I_i + 28EF_{i\,CH_4} \times I_i + 265EF_{i\,N_2O} \times I_i) \tag{5.2}$$

$$WC/VKT = \sum_{i=1}^{N}(WC_i \times I_i) \tag{5.3}$$

$$FFD/VKT = \sum_{i=1}^{N}(FFD_i \times I_i) \tag{5.4}$$

$$LU/VKT = \sum_{i=1}^{N}(LU_i \times I_i \times TO_i) \tag{5.5}$$

Where, $GWP =$ global warming potential in kgCO_2, $VKT =$ vehicle kilometer travelled, $i =$ life cycle inventory input $(1, 2, 3 \dots \dots N)$ per VKT, $I =$ amount of input, $EF_{i\,CO_2} = CO_2$ emission in kg for an input i , $EF_{i\,CH_4=}$ CH_4 emission in kg for an input i , $EF_{i\,N_2O}=$ N_2O emission in kg for an input i, $WC =$ water consumption in cm^3, WC_i = water consumption for an input i in cm^3, $FFD =$ fossil fuel depletion potential in MJ, $FFD_{i=}$ consumption of fossil fuel for input i in MJ, $LU =$ land use in cm^2.a, LU_i = land use for an input i in cm^2, TO_i= exclusive time of land occupation by input i in years.

The considerations in selecting/developing emissions from fuel inputs for estimating corresponding environmental impacts included:

- Australian life cycle inventory emission database (AusLCI) libraries (AusLCI, 2011) developed by Australian Life Cycle Assessment Society (ALCAS) were employed to calculate the emissions corresponding to inputs used during the life cycle stages.
- For the transportation of chemicals and feedstocks, the widely used 30 tonne articulated truck in rural Australia was considered (Barton et al., 2014; Biswas et al., 2008).
- Emission factors for international freight were considered to estimate the emissions for foreign transportation of chemicals and materials from overseas (e.g., urea fertilizers and membrane).
- Eco-inventory emission factors, AusLCI libraries and Western Australian electricity mix were used to estimate emissions from the Li-ion battery, charger, controller, inverter and converter for the electric vehicle.
- US input-output database was used to calculate the environmental impacts from production of farm machinery used during the agriculture of feedstock for ethanol fuel (Biswas et al., 2008).
- The environmental impact of producing USD $1 (1998 price) equivalent farm machinery was available in the software database. In order to use this database, the current price of farm machinery was deflated to the 1998 price and converted to USD using the 1998 conversion factor [USD 1=AUD 1.5875] (Trading Economics, 2019).
- Emission databases, such as Flexi-N fertilizer were developed based on the composition of Flexi N (40% urea, 40% ammonium nitrate and 20% water) (CSBP Fertilizer, 2019).
- The process for enzyme production and water desalination were developed by using AusLCI libraries.

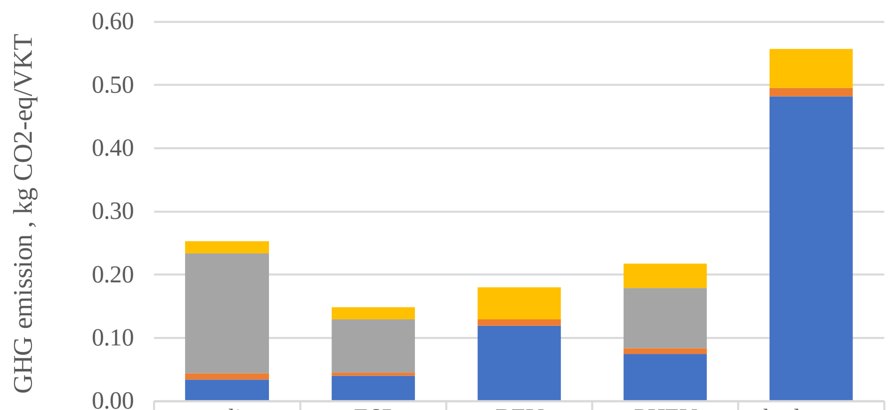
- The libraries for sodium metabisulphite and detergent for desalination were not available in the Simparo databases, so two main ingredients of sodium metabisulphite (sulphur oxide and caustic soda) were used to develop the emission databases for sodium metabisulphite (Biswas, 2009). In the case of detergent products, sodium silicate and sodium metasilicate pentahydrate were used (DIATOM, 2019).
- Although there are emission databases for the Western Australian electricity mix, this was slightly revised using the current electricity mix (Table 2).

Once all the input and output data were linked to the relevant libraries, Simapro calculated the relevant indicators according to the selected impact assessment method. A Monte Carlo simulation (MCS) involving 1000 iterations for a 95% confidence level was conducted to determine the uncertainties of the LCA results associated with the quality of inventory data (Arceo et al., 2019).

5.4 Results and discussions

5.4.1 Global warming potential (GWP)

E65 has the highest GHG emission reduction potential (41%) due to the replacement of gasoline (**Figure 5.3**). Less fertilizer and chemical requirements to grow straw and mallee plus the lower N_2O emission during on-farm/feedstock production were the main reasons for the high GHG reduction potential of ethanol (E65). Since N_2O is a powerful GHG (i.e., 265 times more powerful than CO_2), any reduction of this emission significantly reduces the overall GHG emission. The lack of microbial activity in soil in WA's semi-arid climate, in fact, releases 50-times lower N_2O emissions from the fertilizer application than the IPCC value. **Figure 5.4** shows the breakdown of the GHG emission to identify the hotspot of ethanol production. The conversion of straw to ethanol contributes 70% of the production emissions mainly due to the large amount of GHG emission from enzyme production (i.e., enzyme is considered to be produced on site with ethanol which requires 55% of total conversion emission).



	gasoline	E65	BEV	PHEV	hydrogen
Vehicle	0.019	0.020	0.050	0.038	0.061
Tailpipe	0.190	0.084	0.000	0.095	0.000
Distribution & transportation	0.010	0.005	0.010	0.009	0.013
Fuel Production	0.034	0.041	0.119	0.075	0.482

Figure 5.3: Life cycle GWP (kg$CO_{2\text{-}eq}$/VKT) for different fuel options

Tailpipe emissions were the main dominant factor for GHG emission for gasoline (75% of life cycle emissions) which could be almost eliminated by the use of bioethanol. Any emissions associated with the combustion of plant-based fuel were considered to be sequestered by plants (Stucley et al., 2012). About 29% and 14% of GHGs can be reduced by switching from gasoline to BEVs and PHEVs, respectively, mainly because of the reduction in the tailpipe emission. Like gasoline, tailpipe GHG emission was found to be the hot spot for PHEVs (i.e., 44% of the total life cycle emission). The tailpipe emission PHEV was not completely eliminated as gasoline was used 50% of the total travel time. With the zero scope-1 emission (i.e., tailpipe GHG emission for this case) associated with the electric vehicle, BEVs showed 17% less emission than the PHEVs.

However, GHG emissions from hydrogen fuel (0.56 kg$CO_{2\text{-}eq}$/VKT) were more than double of gasoline which is due to the large amount of electricity consumption during the water electrolysis (i.e., 85% of overall life cycle emission). The emissions during distribution of H_2 were also higher than the other fuels due to the use of heavy tube tankers to carry gaseous fuel. In the case of HFCV, the hydrogen tank (15% GHG emission of HFCV materials) and fuel cell catalysts (18.5% of GHG emission of HFCV materials) were found to be the two main contributors of GHG emissions. The usage of carbon fibre, which is the material of the hydrogen tank could alone contribute to 83% of emissions (i.e., total emission from hydrogen tank is 9.36E-03 kg$CO_{2\text{-}eq}$/VKT and out of which 7.86E-03 kg$CO_{2\text{-}eq}$/VKT from carbon fiber alone) associated with the manufacture of the hydrogen tank. Besides, the use of platinum in the fuel cell catalyst accounted for around 90% emission from the total fuel cell materials emissions. Besides, for the BEV, the battery alone contributed approximately 43.6% emissions of all BEV materials.

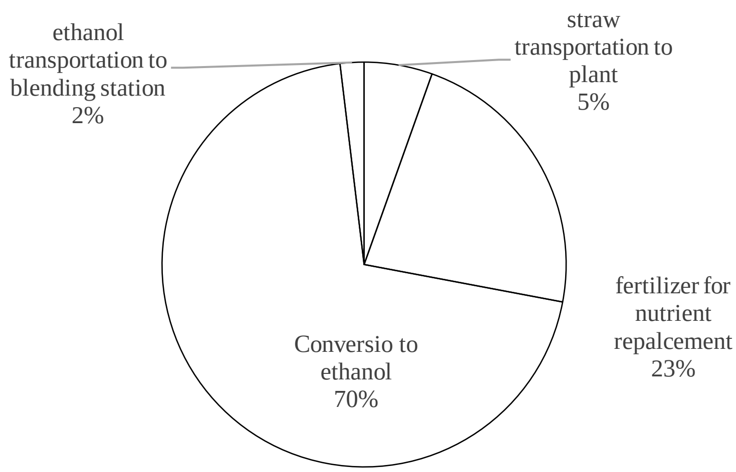


Figure 5.4: Breakdown of greenhouse gas emissions in terms of ethanol (C_2H_5OH) production.

GHG emission results of this LCA were comparable with the existing literature:

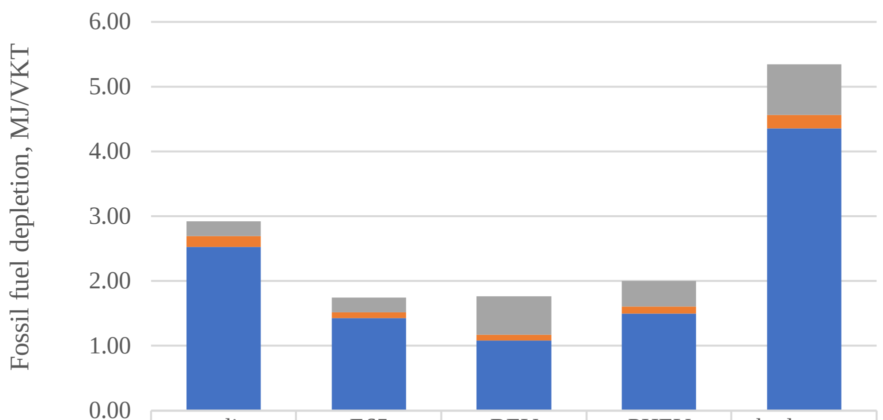
- For example, the GHG emissions for hydrogen fuel production and use in Western Australia for the current study (0.56 $kgCO_{2\text{-}eq}$) is comparable with Biswas et al. (0.67 $kgCO_{2\text{-}eq}$) in 2013 (Biswas et al., 2013b). The GHG emissions of this study were lower due to the fact that it considered the recent WA's electricity mix where the percentage of renewable was higher than that considered previously. Also, it considered the use of a more efficient electrolysis process.
- Emission from GV without taking into account glider emissions (.019 $kgCO_{2\text{-}eq}$ /VKT i.e., total 2122 $kgCO_{2\text{-}eq}$) and HFCV (.061 $kgCO_{2\text{-}eq}$ /VKT) were comparable to Stasinopoulos et al. (total 2137 $kgCO_{2\text{-}eq}$ without glider) (Stasinopoulos, 2016) and Miotti et al. (around .085 $kgCO_{2\text{-}eq}$/VKT with glider) (Miotti et al., 2017) respectively. The GHG emissions for HFCV were higher for the previous study due to the consideration of glider materials.
- The reduction potential of GHG emissions associated with the replacement of an internal combustion (IC) engine with a BEV powertrain of this study (29%) is slightly better than a previous study (22%) (Biswas et al., 2013a) in WA. This small difference mainly resulted from the use of updated energy mix and improved fuel efficiency.

- Like Van Mierlo et al. study in Belgium Van Mierlo et al. (2017) and Sen et al. (2017) in the USA, the current study also found that the PHEV produced higher GHG emissions than the BEV. The GHG emissions from ethanol were also comparable to Wang et al. (2013) and Zucaro et al. (2018).

5.4.2 Fossil fuel depletion (FFD)

Fossil fuel depletion varied from 1.74 to 5.34 per VKT for different fuel options in Western Australia (**Figure 5.5**). Similar to GHG emissions, the fuel production stage was found to be the 'hotspot' for FFD. The overall reductions in fossil fuel depletion due to the use of E65, BEV and PHEV as a replacement for the gasoline engine were 40%, 39% and, 31%, respectively. For E65, the fuel production and distribution accounted for 87% of the total FFD, mainly because of the additional heat required for dehydration of the wheat-based ethanol conversion and enzyme production during lignocellulosic conversion (i.e., straw and mallee to ethanol). Hydrogen fuel, however, showed 83% higher fossil fuel depletion compared to gasoline. Hydrogen production and distribution alone contributed 85.5% of the FFD (among which 94% was from the electricity requirement for water electrolysis and 5% from hydrogen distribution). Since, the desalination plant water supply for electrolysis is 100% run by renewable electricity, this input is not contributing FFD. Like GHG emissions, the use of carbon fibre in the hydrogen tank (27% of HFCV) and platinum in the fuel cell catalyst (16% of HFCV) were mainly responsible for the FFD for the HFCV as those were manufactured by using conventional fuel.

FFD of BEV was 39% lower than gasoline due to the use of a cleaner electricity mix (only 28% from low efficient coal, around 7.5% renewable, 53% from natural gas) as fuel. Fuel production and distribution for the BEV accounted for 66% of the FFD compared to 34% for the BEV materials. The battery was found to be the highest FFD consumer (46% of the BEV materials) mainly due to the production of the Li-ion battery cell. The FFD associated with the use of the PHEV, on the other hand, were found to be 13% higher than the BEV as the latter relies on gasoline for 50% of the travel time.



	gasoline	E65	BEV	PHEV	hydrogen
Vehicle	0.23	0.23	0.60	0.40	0.78
Distribution & transportation	0.17	0.08	0.09	0.11	0.21
Fuel Production	2.53	1.43	1.08	1.50	4.36

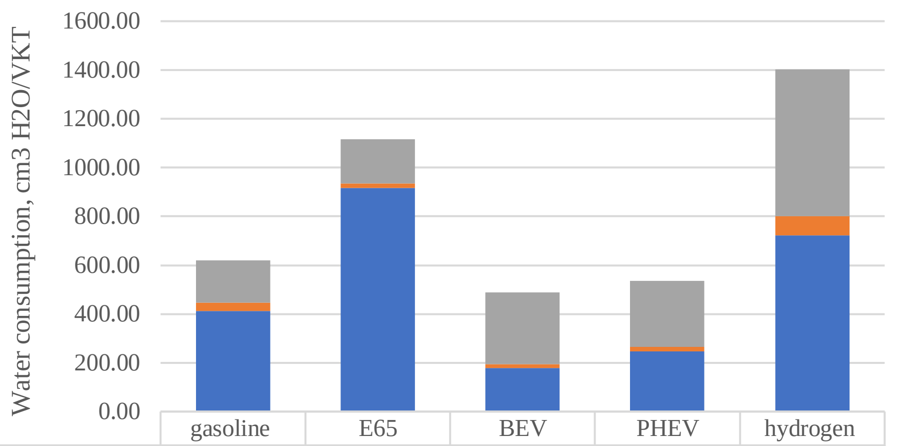
Figure 5.5: Fossil fuel depletion for different fuel options (tailpipe emissions are omitted as there were no FFD associated with tailpipe emissions)

In the absence of studies that considered FFD as an indicator for assessing alternative fuels, it is quite complex to compare the LCA results of products derived from a biological system for one particular region in comparison with another. This is primarily due to the difference in climate conditions and resource use (Hoque et al., 2020b). Despite this, some comparisons with the existing literature have been made as follows:

- Cavalett et al. (2013) showed that E100 (100% ethanol) from sugarcane in Brazil produced 5 times lower FFD than the gasoline, while E65 containing 35% fossil fuel (i.e., gasoline) in this study produced almost 1.67 times lower FFD than the gasoline.
- In addition, the electric vehicle in different European countries reduced FFD impact between 25% to 36% depending on the electricity grid (Hawkins et al., 2013) which was comparable with the current study (i.e., 39% for the BEV and 31% for PHEV).

5.4.3 Water consumption (WC)

Life cycle water consumption was calculated based on the water use for different activities over the life cycle of the fuel. E65 showed lower water consumption (1117 cm^3 /VKT) than hydrogen as main feedstock (i.e., straw) for ethanol was the byproduct of grain production and WA's grain production was rainfed. As shown in **Figure 5.6**, the production stage of E65 still consumed 82% of the life cycle water use. This higher water consumption was due to the direct water requirement during the conversion of ethanol from lignocellulosic feedstocks. Ethanol conversion from straw and mallee wood contributed around 86% and 94% of water consumption during the production stages. Besides, the manufacture of fertilizers in the pre-farm stage accounted for 69% of water consumption of production stage for wheat-based ethanol.



	gasoline	E65	BEV	PHEV	hydrogen
Vehicle	171.60	180.97	295.38	269.10	603.26
Distribution & transportation	34.05	19.42	15.49	20.70	77.74
Fuel Production	413.55	916.11	178.58	245.68	722.58

Figure 5.6: Water consumption impact for different fuel options (tailpipe emissions are omitted as there are no WC associated with the tailpipe emission)

WC for hydrogen fuel was 1404 cm^3 /VKT without considering the seawater for electrolysis. Hydrogen production and distribution accounted for 57% of the total life cycle water consumption and the remaining 43% were from HFCV. The reason for high water consumption during hydrogen production was the large amount of electricity (54 kWh/kg of H_2; i.e., 1310 cm^3 H_2O/kWh) requirement during water electrolysis. Besides, higher WC for HFCV primarily due to the use of NiMH battery (around 22% of HFCV WC) and platinum catalyst (around 22% HFCV WC) in the fuel cell. However, after adjusting the production stage water consumption (i.e., 9 kg/kg H_2) of hydrogen fuel by including seawater in the impact assessment, the total WC of hydrogen fuel was 1494 cm^3/VKT.

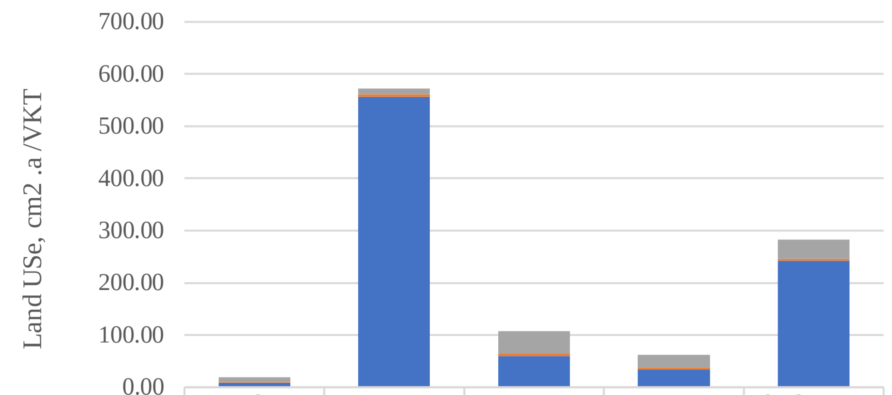
Unlike E65 and hydrogen fuel, WC per VKT for gasoline (619 cm^3), BEV (489 cm^3) and PHEV (535 cm^3) were found to be closer. The vehicle materials (i.e., changes in vehicle to enable electricity as fuel compared to gasoline) account for 60% WC for the BEV compared to 40% in fuel production mainly due to the high-water requirement during the production of the battery and other electronic components such as the inverter, converter and electric motor. The life cycle water consumption of PHEV was slightly higher than BEV as the production and distribution of the gasoline (i.e., gasoline was used 50% of the total travel time of PHEV) required more water than that used to generate electricity in WA.

The WC for gasoline production for this study was similar to the findings of Sun et al. (2018). Besides, Wu and Xu (2018) showed that WC for ethanol production from corn was 1.6 to 57 times higher than gasoline depending on water requirements for irrigation. The water consumption of E65 of this study was around 1.80 times higher than gasoline because the percentage of C_2H_5OH in the blend was low which means that a small amount of water was required for irrigation for growing C_2H_5OH feedstock. In addition, farmers in WA rely on rainfed agriculture (Barton et al., 2014). Sharma and Strezov (2017) showed that production of hydrogen consumed 1.5 times more water than gasoline (without considering vehicle) per km. Therefore, the finding of 2.41 times higher WC than gasoline for this study is comparable due to the consideration of WC for distribution of hydrogen and vehicle materials.

5.4.4 Land use

Land use impact (cm^2.a/VKT) was measured as a total use of the land for a given period of time for occupation by the built environment, forestry production and agricultural production processes (Carre, 2011). As shown in **Figure 5.7**, the fuel production phase dominated the land use impact for E65 and for hydrogen fuel. E65 showed the highest land use impact (i.e., 572 cm^2.a/VKT) due to the requirement of land to grow feedstocks. For example, the production of wheat and mallee accounted for 99% and 93% land use, respectively, during the farming stage. Similarly, hydrogen production and distribution contributed to 87% of land use impact, which is due to the use of land to generate electricity during water electrolysis.

For the BEV, however, 39% of land use occurred from vehicle materials as well as 61% from fuel production. The higher land use from fuel production was due to land use in the upstream processes of electricity generation. On the other hand, the land requirement for BEV battery accounts for 49.32% of the land used for all materials. This is due to the use of land for mining, processing and manufacturing of materials for batteries. The PHEV requires almost half of the land compared to the BEV, which would be due to the use of gasoline fuel to complete 50% of the journey. It should be noted that electricity production requires more land than gasoline production and supply due to the infrastructural requirements.



	gasoline	E65	BEV	PHEV	hydrogen
Vehicle	10.18	10.91	41.95	25.01	37.60
Distribution & transportation	0.63	4.74	5.19	2.95	3.63
Fuel Production	8.16	556.04	59.85	34.31	241.92

Figure 5.7: Land use impact for different fuel options (tailpipe emission is omitted as there is no land use impact associated with tailpipe emission)

Compared to gasoline, E65, hydrogen, BEV and PHEV required 30.13, 14.92, 5.64, 3.28 times more land, respectively, being comparable to the results published in other studies. As there was no study on the land use impact for different fuel options in WA, the results were compared with the studies on other regions. For example, Sharma and Strezov (2017), found that E85 and hydrogen require 350 and 1.24 times more land than that of gasoline per VKT. In this study, the land use of E65 was low, because it considers a lower blended ethanol (i.e., 65% ethanol compared 85% in the previous study) and main ethanol feedstock for this study (i.e. straw) for this study is a byproduct of wheat production. Land use impact for hydrogen, however, is higher for this study due to the consideration of land required for mining, process and manufacturing of vehicle materials. Besides, land use for BEV was lower than hydrogen due to having less electricity requirement per VKT and the lower materials requirements compared to HFCV.

5.5 Uncertainty analysis

Uncertainty analysis was based on 1000 iterations for a 95% confidence level. The mean value of calculated result and coefficient of variance (CV) of each indicator are shown in **Table 5.8**. The CV values ranged between 1.36 and 25.95. The relatively smaller CV was obtained for the global warming potential (1.36 to 2.99), which was indicative of a lower degree of uncertainty as there was no direct effect from the land use change, vegetation and topography (Arceo et al., 2019). Nonetheless, higher variations in the CV values were observed for the land use category (0.43 to 25.92) due to the aforementioned factors. The difference between the calculated value and mean for all impact categories was also found to be quite small, which varied between 0.4% and 5.82%.

Table 5.8: Uncertainty analysis (based on FU per VKT).

Indicators	Parameters	Gasoline	E65	BEV	PHEV	Hydrogen
GWP ($kgCO_2$)	Calculated Value	0.25	0.15	0.18	0.22	0.56
	Mean	0.25	0.15	0.17	0.21	0.55
	CV	1.47	1.6	2.99	1.36	2.98
FFD (MJ)	Calculated Value	2.92	1.74	1.77	2.00	5.34
	Mean	2.88	1.70	1.71	1.93	5.27
	CV	2.24	1.82	2.69	1.71	2.44
WC (cm^3 H_2O)	Calculated Value	619	1117	489	535	1409
	Mean	610	1115	479	522	1407
	CV	6.15	4.3	5.45	3.74	6.76
Land Use (cm^2. a)	Calculated Value	18.97	572	107	62	283
	Mean	17.82	572	106	61	282
	CV	20.19	0.43	19.5	18.43	25.92

5.6 Conclusions

This chapter has investigated the environmental performance of potential fuel options for Western Australia using the life cycle assessment framework. Alternative fuel options, such as E65, BEV, PHEV and hydrogen were selected based on local resource availability. The study has compared these fuels with the fossil fuel gasoline as a reference case. Four indicators, namely GWP, FFD, WC and land use were considered based on their necessity that was established through the literature review and expert surveys. Monte Carlo simulation statistical analysis was conducted to ascertain the reliability of the results.

The results indicated that the BEV and PHEV have the potential to reduce the GHG emission, FFD and WC impact when compared to gasoline. That was mainly due to the reduction of tailpipe emissions and the use of cleaner electricity. Since hydrogen production is reliant on large amounts of electricity, it has a higher environmental impact in all the impact categories compared to that of gasoline. The requirement of heavy tube tankers for hydrogen distribution and use of carbon fibre in the hydrogen tank and platinum in the fuel cell in the HFCV are also responsible for the higher impacts from hydrogen. Ethanol (E65), however, outperformed all other fuel options in terms of GWP impacts due to its low environmental burden during feedstock production but produced higher WC impacts similar to the ones from hydrogen. Land use impact was also the highest for E65 followed by hydrogen, BEV, PHEV and gasoline. The highest land use impact associated with E65 was due to the land requirement during the agriculture of ethanol feedstocks. In terms of vehicle materials, the BEV (41% of total life-cycle land use) had the highest land use impact that is predominantly due to the battery production.

Feedstocks for the study were selected in such a way that their use in the production of fuel(s) had minimal or no effect on the food supply chain in WA. The state also has an enormous amount of land which is capable of supporting renewable power production and alternative fuel activities. Adoption of renewable resources may reduce the environmental burden due to extensive fuel use, especially with hydrogen and electric vehicles in the state. However, future research regarding sustainability evaluation of these fuel options may need to incorporate social and economic aspects.

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Chapter 6

Implementation of Framework: Socio-economic Assessment and Execution of Framework

Abstract

Environmental obligation, fuel security, and human health issues have fuelled the search for locally produced sustainable transport fuels as an alternative to liquid petroleum. This study evaluates the sustainability performance of various alternative energy sources, namely, ethanol, electricity, electricity-gasoline hybrid, and hydrogen, for Western Australian Road transport using a life cycle sustainability assessment (LCSA) framework. The framework employs 11 triple bottom line (TBL) sustainability indicators and uses threshold values for benchmarking sustainability practices. The indicators are selected based on the rigorous literature review and experts' opinion. A number of improvement strategies were devised based on the hotspots once the alternative energy sources failed to meet the sustainability threshold for the determined indicators. The proposed framework effectively addresses the issue of interdependencies between the three pillars of sustainability, which was an inherent weakness of previous frameworks. The results show that the environment-friendly and socially sustainable fuel options, namely, ethanol-gasoline blend E55, electricity, electricity-E10 hybrid, and hydrogen, would need around 0.02, 0.14, 0.10, and 0.71 AUD/VKT of financial support, respectively, to be comparable to gasoline. Among the four assessed options, hydrogen shows the best performance for the environmental and social bottom line when renewable electricity is employed for hydrogen production. The economic sustainability of hydrogen fuel is, however, uncertain at this stage due to the high cost of hydrogen fuel cell vehicles (HFCVs). The robustness of the proposed framework warrants its application in a wide range of alternative fuel assessment scenarios locally as well as globally.

6.1 Introduction

Concerns regarding climate change along with related health issues, increasing expenses of non-renewable energy sources, and the geopolitical vulnerability related to fossil fuel supplies have propelled countries to look for clean and renewable substitutes (Hoque et al., 2019a; Roy and Dutta, 2013; Roy et al., 2012). Engineers need to search for region-specific alternative fuel sources to improve the environmental, economic, and social situation (Hoque et al., 2019b; Roy and Dutta, 2013; Tucki et al., 2019).

In Australia, the transport sector consumes the highest share of energy (1589.2 PJ, 27.3%) compared to all other sectors in the country (Department of Industry and Science, 2015). The sector is mainly dependent on fossil fuels and accounts for 16% of total Australian greenhouse gas (GHG) emissions. The Australian transport sector could face serious energy security issues if there is a substantial fluctuation in price and/or geopolitical conflicts due to the fact that 90% of its transport fuel is imported through different conflict zones (Blackburn, 2014). The strategic petroleum reserve of Australia is quite low compared to other OECD countries. The country, for example, currently holds only 18 and 22 days of cover for petrol and diesel fuel requirements, respectively (Commonwealth of Australia, 2019).

Reference (Hoque et al., 2019a) reveals that the transportation system in Western Australia (WA) is unsustainable. Mining, which is the life blood of WA's economy, has almost the same energy consumption as the transport sector (Government of Western Australia, 2018). This is because people are heavily dependent on passenger cars, and the use of public transport is not popular due to the dispersed locations within WA and long distances between population centres (Biswas et al., 2013). A 20-minute journey by car in Perth (capital of WA), often takes more than an hour by public transport, which usually requires bus and/or train changes (Wynne E, 2017). About 78% of WA's vehicles are passenger cars, of which 87% use imported gasoline. WA's transport fuel contributes quite a large share (14%) of the state's GHG emissions (Biswas et al., 2013; Chapple, 2012). Low-elevation vehicle exhaust emissions in the atmosphere have the potential to cause significant human health problems (Renouf et al., 2015). The UK and France have already declared a ban on the sale of gasoline and diesel cars from 2040 to combat air pollution and health problems (Chrisafis and Vaughan, 2017; Roger, 2017). The use of locally available alternative fuels needs to be explored for the passenger vehicles in WA to overcome the aforementioned socio-economic and environmental issues (Bureau of Transport and Regional Economics, 2005). Life cycle sustainability assessment (LCSA), which considers all three aspects of sustainability during the entire life cycle of fuel, is a very useful tool for making realistic decisions (Hoque et al., 2019b).

A review of the sustainability assessment of alternative fuels (Chapter 2) showed that 62% of the published studies considered only the environmental life cycle assessment (ELCA), whereas 25% considered ELCA and life cycle costing (LCC) (Hoque et al., 2020). The literature on social life cycle assessment (SLCA) and LCSA of alternative fuels is still very limited (Hoque et al., 2020). The assessment of alternative fuels using the triple bottom line (TBL) sustainability indicators has not been done rigorously (Hoque et al., 2019b). The decision to choose sustainable alternative fuels is primarily dependent on the sources of locally available feedstocks and their long-term availability (Hoque et al., 2019a). Besides, sustainability indicators need to be selected based on local requirements (Hasan et al., 2020; Hoque et al., 2020; Lim and Biswas, 2019). A few studies (Akber et al., 2017; Keller et al., 2015; Li et al., 2017; Osorio-Tejada et al., 2017b; Santoyo-Castelazo and Azapagic, 2014) in different sectors, such as fuel, electricity, bio-refineries, and application of solar energy, applied multi-criteria decision-making techniques to combine the three objectives of sustainability based on different weighting approaches, but a scenario analysis with regard to interdependencies between the TBL indicators was absent (Hoque et al., 2020). Practical case studies that incorporate the three dimensions of sustainability with life cycle approaches to operationalizing the concept of LCSA are required (Guinée, 2016). A comprehensive framework is presented in Chapter 3 based on previous studies by the author (Hoque et al., 2019b). The framework includes all the relevant phases of a product's life cycle as well as regional scale fuel selection and indicator development. The framework also accommodates scenario analysis, incorporating interdependencies among the three pillars of sustainability in order to overcome the weaknesses in other studies.

The first stage of implementing the analysis was to conduct the environmental component of the framework (Chapter 5), which has already been published (Hoque et al., 2019a). The second step is the full execution of the framework by integrating SLCA and LCC with ELCA of alternative fuel sources, which is presented in this chapter. In addition, the study presents threshold values for sustainability indicators, which were developed to identify hotspots and incorporate improvement strategies into the framework for identifying sustainable fuel options. The study presents a novel approach to evaluating alternative fuels using Hoque et al.'s framework (Hoque et al., 2019b) which proposed incorporating the TBL of sustainability, threshold values, and a life cycle approach.

6.2 Execution of the framework

This section discusses various aspects of the framework such as fuel selection, indicator selection, process for data collection and evaluation, and the development of threshold values for sustainability decisions to present the implementation process of the framework under the goal and scope of the study.

6.2.1 The framework

The LCSA framework, as shown in Figure 3.1 (Chapter 3), has been used to assess the triple bottom line sustainability performance of alternative fuels. ELCA, SLCA, and LCC tools are integrated into the framework to measure the environmental, social, and economic indicators of the selected fuel options. The selection of appropriate TBL indicators, determination of threshold values, data collection, sustainability assessment, , hotspot analysis, and selection of proper improvement strategies are the main constituents of the framework. In order to aid the decision making for sustainable fuel selection, the framework employs a threshold value approach for estimating the level of sustainability performance achieved. Once the TBL metrics have been determined, the findings are compared with the applicable threshold values to verify that the sustainability requirements have been met. The possible causes for not meeting the sustainability performance are then investigated through hotspot analysis. Accordingly, TBL improvement strategies are incorporated into the framework to meet the threshold value.

According to the framework, fuel options are considered for social assessment only if all the ELCA indicators satisfy the threshold values. This is followed by economic assessment, which is the third phase of the sustainability assessment of the selected fuel options. A similar process is applied to the economic assessment, as social sustainability has to be met prior to considering the economic analysis. Follow-up ELCA, SLCA, and LCC analyses are conducted after incorporating environmental, social, and economic improvement strategies to ascertain and address the interdependencies between TBL indicators. Application of renewable energy during the production of alternative fuel, utilization of cleaner electricity for electric vehicle charging, local production of alternative fuel vehicle components, etc., are some examples of environmental and social strategies that have been employed in this study. Other than that, different policy instruments, such as rebates, capital subsidy, research and development, soft loans, etc., are examples of incorporated economic strategies.

6.2.2 Goal and scope definition

The goal of this LCSA study is to determine the sustainability performance of alternative fuels for the Western Australian transport sector. The functional unit of the study is vehicle kilometre travel (VKT), and the system boundary includes all stages of the fuel life cycle from resource extraction to use in the vehicle (i.e., well to wheel). Furthermore, any modifications in the internal combustion engine and powertrain for enabling the use of alternative fuel are included in the TBL assessment. The gliders of all vehicle types are considered the same (Hoque et al., 2019a; Miotti et al., 2017; Notter et al., 2010; Sharma et al., 2013). The end-of-life stage of the vehicle was not considered as the study focused on the fuel life cycle only. The vehicle maintenance phase was also excluded due to its insignificant (1–2%) contribution to the life cycle impacts (Hoque et al., 2019a; Sharma et al., 2013; Stasinopoulos, 2016).

6.2.3. Fuel selection

Fuel selection for the region, which is the first step in the framework, entirely depends on the availability of the relevant feedstocks. There would be additional environmental impacts and costs if the feedstocks were to be imported from other places. Chapter 4 covers the detail discussion regarding the selection of these fuel options. Keeping in mind the availability of feedstocks in WA, alternative fuel options, such as E65 (ethanol-gasoline blend: 65% ethanol), electricity for battery electric vehicle (BEV), electricity-gasoline for plug-in hybrid electric vehicle (PHEV), and hydrogen, have been selected initially for the assessment as an alternative to gasoline for WA's gasoline-driven passenger vehicles (Hoque et al., 2019a). For the ethanol fuel (E65), three potential feedstocks, namely, wheat (10%), cereal straw (53%), and mallee (2%), were considered.

6.2.4 Selection of TBL indicators for LCSA

The development of region-specific TBL indicators is required for conducting a more reliable sustainability assessment (Lim and Biswas, 2015; Lim and Biswas, 2017). For this study, initially, 13 indicators (Environmental: global warming potential, fossil fuel depletion, water consumption and land use; Social: local job creation, occupational health and safety, conservation of fossil fuel and human health; Economic: life cycle cost, carbon reduction credit and net benefit) were selected based on a critical review of the local data and literature. Local reports from related government and semi-government organizations, such as the Australian Renewable Energy Agency (Australian Renewable Energy Agency, 2016), Australian Life Cycle Assessment Society (Renouf et al., 2015), Department of Agriculture (Carre, 2011), Commonwealth Scientific and Industrial Research Organization, etc., and published studies were reviewed. Some of the environmental indicators, for example, human toxicity, ozone depletion potential, acidification, and biodiversity, were excluded due to their rather low impact in WA (Hoque et al., 2019a; Renouf et al., 2015). The reason for inclusion (or not) of environmental indicators were described in the previous chapter.

Vehicle exhaust emission, as a measure of human health has been considered an important indicator for the social sustainability assessment of alternative fuel in this study, as direct exposure to low-elevation vehicle emissions can cause serious harm to human health (Hoque et al., 2019a). Three exhaust emissions from the vehicle, namely, CO, PM, and NO_x, were considered on the basis of the main air contaminates in WA, their sources from vehicles, and possible health impacts (Government of Western Australia, 2018). Besides, local job creation was considered as an important measure for any alternative fuel in Australia (O'Connell et al., 2007). There are ties between social and economic impacts as social development also increases economic activity (O'Connell et al., 2007). The 'local job creation' indicator has been considered under the social dimension of sustainability in the current study, following the existing literature (Akber et al., 2017; Ekener-Petersen et al., 2014; Onat et al., 2014; Osorio-Tejada et al., 2017b; Souza et al., 2018; Yu and Halog, 2015) and guidelines such as the social hotspot database (Ekener-Petersen et al., 2014), Organization for Economic Co-operation and Development indicators (OECD, 2016), and Global Bioenergy Partnership sustainability indicators (Food and Agriculture Organization of the United Nations, 2011). Conservation of fossil fuel is selected as a social indicator in addition to the FDD as an environmental indicator following the articles of Santoyo-Castelazo & Azapagic (2014); Akber et al (2017); Atilgan & Azapagic (2016) and Akber et al (2017) due to the local requirements of WA. Transport industry in Western Australia is heavily reliant on imported fossil fuel (97% of its vehicles use imported traditional liquid fossil fuel). Long-term energy security of liquid transport fuel can be an issue in WA as the state heavily relies on international supply chain, difficult sources and geopolitically risky supply (Department of Resources Energy and Tourism, 2011; John, 2014). So, reducing the of use of imported fossil fuel for transportation will provide the long-term transport fuel security to the state (WA), reduce the fuel import, and conserve fossil fuel for future generations. That is why, conservation of fossil fuel is also deemed as an important indicator for sustainability assessment of alternative fuel in WA.

To establish the indicators for this study, expert opinion was gathered through a survey. Obligatory ethics approval had to be obtained from Curtin University (approval number: HRE 2019-0101) before launching the survey. The survey was conducted over 6 months from March 2019 to August 2019 by using an online questionnaire. In total, 30 responses were collected from three stakeholder categories, namely, academia, industry, and government, where each category provided an equal number of responses (i.e., 10 responses were collected from each category). The indicators that were considered important by 50% or more of the experts were selected for assessment. Experts were also given an option of suggesting new indicators.

Finally, four environmental, four social, and three economic indicators were selected through consensus conference, as shown in **Table 6.1.**

Table 6.1: Selected triple bottom line (TBL) indicators for the study

Sustainability Dimension	Indicators	Unit	Percentage of Respondents that Considered it Important
Environmental	Global warming potential (GWP)	Kg CO_2/VKT	87%
	Fossil fuel depletion (FFD)	MJ/VKT	67%
	Water consumption (WC)	m^3/VKT	63%
	Land use (LU)	Ha.a/VKT	53%
Social	Local job creation *	man.hour/VKT	67%
	Conservation of fossil fuel (CFF)	MJ/VKT	50%
	Occupational health and safety (OHAS)	Qualitative	50%
	Human health based on vehicle exhaust emission (HH_{VEE}) **	gm/VKT	86%
Economic	Life cycle cost	AUD/VKT	83%
	Carbon reduction credit (CRC)	AUD/VKT	57%
	Net benefit (benefit of using alternative fuel compared to gasoline)	AUD/VKT	70%

* Direct job creation locally in WA due to local activities within the system boundary.
** Only vehicle exhaust emission is considered due to its direct impact on human health and its requirement for local policy formation in WA (O'Connell et al., 2007).

Even though social acceptability was included in the beginning as a social indicator based on some previous studies (Osorio-Tejada et al., 2017a; Weldegiorgis and Franks, 2014), it was later excluded based on the respondents' suggestions. The survey respondents commented that the cost competitiveness of alternative fuels (e.g., life cycle cost) was the critical factor in fuel selection in WA rather than social acceptability. Social implications may arise due to grain-based ethanol production but the main ingredient of ethanol in this study was cereal straw, which remained as an unused by-product (Stucley et al., 2012). Mallee trees, on the other hand, are an inedible source that was proposed to be grown on the terraces of the agriculture fields without disturbing the existing agricultural practices (Stucley et al., 2012). Only a small portion of wheat that would be enough to produce an E10 requirement for WA has been conservatively considered to prevent food scarcity issues (Hoque et al., 2019a). The amount of wheat needed for E10 production is trivial as only the starch part of the wheat, which accounts for around 20% of the wheat, is used for ethanol production and the remaining 80% returns to the food supply chain as a distiller grain (United Petroleum, 2018). Similarly, eutrophication was removed because it was not considered relevant by the local experts due to its minimal effect on the alternative fuel supply chain in WA (Hoque et al., 2019a). Using the same rationale, the impact of the use of feedstocks for ethanol fuel production was ignored even though it was suggested as an indicator by some of the survey respondents.

6.2.5 Data collection and assessment procedures

This section presents how the data were collected and used in the ELCA, SLCA, and LCC analyses to calculate TBL indicators.

Environmental indicators

The detailed data regarding the selected ELCA indicators have already been presented in the previous chapter. As mentioned in the Table 6.1 four indicators such as GWP, FFD, LU and WC are selected for the analysis.

Social indicators

Alternative fuels have the potential to create jobs locally (O'Connell et al., 2007). Direct local job creation due to the manufacturing and activities related to the input and output processes required over the life cycle of the alternative fuel was measured (**Equation 6.1)** in this study as job creation/VKT. By considering WA's current vehicle industry competence (Government of Western Australia, 2019a; Hastie, 2019) and following the case of WA's neighboring state South Australia (Energy Matters, 2019), the assembly of alternative vehicles that use alternative fuels was assumed to take place locally in Western Australia.

$$Local\ Job\ creations/VKT = \sum_{i=1}^{N} (mh_i \times I_i) + mh_{P+}\, mh_{va} \qquad (6.1)$$

Where, $i =$ life cycle inventory input $(1, 2, 3 \ldots \ldots N)$ which comes from local WA per VKT, mh_i = man-hours required for input i, $I =$ amount of input, mh_P = man-hours required at the alternative fuel production plant to produce 1 km equivalent alternative fuel, mh_{va} = man-hours required at the vehicle assembly plant to assemble 1 km equivalent alternative vehicle.

Other assumptions for estimating the local job creation were as follows:

- Person-hours required per unit of inputs (e.g., production of herbicides, fertilizers, etc.) were calculated by collecting data from local plants/organizations. For example, fertilizer was required during the cultivation of ethanol feedstocks. The number of staff required to produce each unit of fertilizer was collected from Perdaman Industries located in Karratha, WA. To produce 2 million tonnes of fertilizer per annum, the producer would require around 200 permanent staff (Perdaman Industries Chemical and Fertilizers, 2017). Therefore, the calculated man-hours for this input were 1.79×10^{-4} for per kg of fertilizer by considering standard working hours of 34.4 per week for Australia (Rustandi and Wu, 2010). Job creation through plant construction (e.g., plants to produce fertilizers, electricity, etc.) were not considered as these plants were not solely constructed to produce inputs for alternative fuels.

- Job creation related to other activities, such as seeding, spraying, and harvesting during the farming stage of ethanol (**Appendix-D: Table A-1**), were calculated based on local data published in various studies (Biswas et al., 2008; Stucley et al., 2012; Weldegiorgis and Franks, 2014; Wu et al., 2007) and information received from the Department of Primary Industries and Regional Development (Department of Primary Industries and Regional Development, 2018). Staff requirements for the ethanol production plant (e.g., 1.17×10^{-3} man-hours/L for cellulosic ethanol) were taken from AECOM Australia (AECOM Australia, 2016), whereas the data for the hydrogen production plant (e.g., 4.48×10^{-3} man-hours/kg H_2) were based on American industries (Miller et al., 2017) due to the unavailability of local data.

- The measurement of job creation per kWh of electricity generation is quite complex because the electricity is produced from a number of fuel sources. For locally inaccessible information, **Equation 6.2** (Akber et al., 2017; Rutovitz et al., 2015) was used to generate the data by using the electricity mix of WA. Job creation during the fuel extraction and plant operation phases were taken into account because of the direct influences of these phases on the local job market. The job creation per kWh was calculated as 1.90×10^{-4} man-hours/kWh. Distribution phases of all fuels were assumed to create the same number of jobs based on the estimation by Garrett-Peltier (2012).

$$\text{Job creation through electricity} = \mathrm{I_c} \times \mathrm{J_f} \times \mathrm{M} \tag{6.2}$$

Where, I_c = Installed capacity, J_f = employment factor estimated from Rutovitz et al. [25] and M = multiplier (1 for OECD pacific countries such as Australia for this instance).

- The Altona vehicle assembly plant in Australia employed 4000 staff for the assembly of 61,000 cars per year (ABC News, 2017). Based on this information and the average life of 112,567 km for a passenger vehicle in WA (Hoque et al., 2019a), the job creation through vehicle assembly per km has been calculated. Assembly of a BEV would require 30% less time compared to gasoline due to there being fewer moving parts in the drive train (Gustafson, 2019). A hydrogen fuel cell vehicle (HFCV), on the other hand, requires more time to assemble due to the use of complex technologies (i.e., fuel cells and safety devices). However, the assembly time is expected to reduce with mass production and improvements in automation, as has occurred with the gasoline engine (Harding and Inagaki, 2017; Sørensen, 2012). The time required for assembly also varies with the size of the plant, number of cars produced per year, and vehicle model (Toyota, 2019). The job creation through vehicle assembly was thus assumed to be the same for all vehicles to provide a fair comparison.

The conservation of fossil fuel (CFF) by using an alternative fuel was measured using **Equation 6.3**. Human health, on the other hand, was assessed based on the difference in the exhaust emissions of gasoline and alternative fuel vehicles per VKT as mentioned during the indicator selection section. For the qualitative indicator (i.e., occupational health and safety, OHAS), a 5-point Likert scale was used to collect scores from the respondents in the supply chains of alternative fuels, where 1 indicated the least satisfaction and 5 indicated 100% satisfaction (Hoque et al., 2019b; Lim and Biswas, 2017). If any respondent scored less than 5, the reason was asked (or what would make them score 5) (Hoque et al., 2019b). Approval regarding the survey from Curtin University Human Research Ethics Committee (**Appendix-C**) was received in September 2019. The survey was conducted over a period of eight months from September 2019 to April 2020 to collect the responses.

$$CFF/VKT = FFD_{af} - FFD_{gasoline} \tag{6.3}$$

Where, CFF = Conservation of fossil fuel in MJ, FFD_{af} = Fossil fuel use of alternative fuel per VKT in MJ, $FFD_{gasoline}$ = Fossil fuel use of gasoline per VKT in MJ.

<u>Economic indicators</u>

The cost data are summarized in **Appendix-D: Table A-2**. The base year for economic analysis was 2018, and the costs for other years were either inflated or deflated to 2018 AUD. The following considerations were made during the calculation of economic indicators:

- Assumptions regarding the cost per unit of corresponding traditional fuel is one of the deciding factors for the sustainability assessment of alternative fuels. The gasoline price was close to 150 cents/L in 2013 and decreased afterwards but started to increase again in 2018 (Fuel Watch Western Australia, 2020). To capture this variation, the average gasoline price (135.42 cents/L) for the last 7 years was considered (Fuel Watch Western Australia, 2020).
- Zero economic allocation was provided to cereal straw during the environmental assessment (Hoque et al., 2019a). This was done because the cereals were solely cultivated for food production in WA and, therefore, no cost was allocated for straw production. However, costs associated with straw harvesting, handling, nutrient replacement, and transportation of straw to the processing plant were considered. Additionally, a nominal profit margin of around 11 AUD/tonne of straw was considered for the farmers for their contribution to bioenergy (Stucley et al., 2012).
- The cost relating to different activities for growing mallee in WA was based on the studies by Wu et al. (2007) and Stucley et al. (2012). This is shown in **Appendix-D: Table A-2.** The estimated cost of mallee production was around 53.45 AUD/green metric tonne.
- The capital cost of ethanol plants was calculated based on a 100 ML/year capacity facility with a project life of 20 years (AECOM Australia, 2016). The capital cost for starch and cellulosic (i.e., straw in this study) ethanol plants in Australia was assumed to be AUD 97 M and AUD 194 M, respectively (AECOM Australia, 2016).
- A 50,000 kg/day hydrogen production plant (approximately equivalent to ethanol plant capacity) with a project life of 35 years was considered (Bruce et al., 2018; Miller et al., 2017). An initial capital cost of around 144 M AUD for the hydrogen plant was assumed based on an estimation by the Commonwealth Scientific and Industrial Research Organization Australia (Bruce et al., 2018). With the initial investment, a 15% replacement cost was assumed every 7 years due to the fuel cell stack (Miller et al., 2017). All the capital costs were based on 100% debt with 7% interest rate over the life cycle of the project (Bruce et al., 2018).
- The costs of utilities, such as electricity, water, and gas, for different purposes are shown in **Table 6.2**. Water price for non-residential customers varies in WA due to the associated cost of supplying water in different regional locations (WA Water Corporation, 2019). The

electricity costs of hydrogen and ethanol plants were based on the price for industrial customers received from a local supplier, Synergy (Synergy, 2019).

Table 6.2: Cost of utilities for different activities.

Items	Unit	Cost/Unit	Purpose	Reference
Electricity	AUD/kWh	0.2011 * (of which the first 10 unit/month is free)	BEV and PHEV home charging	Synergy (2019)
Electricity		0.5274 (peak) 0.1584 (off-peak)	Ethanol and hydrogen production plant	Synergy (2019)
Desalinated water	AUD/kL	1.17	Hydrogen plant at KIA	Water Technology (2019)
Water for business utility at Northam		7.221	Ethanol from cereal plant	WA Water Corporation (2019)
Water for business utility at Katanning		8.562	Ethanol from mallee plant	WA Water Corporation (2019)
Water for business utility at KIA		3.653	Ethanol from wheat	WA Water Corporation (2019)
Natural gas (for heating during wheat based ethanol production)	AUD/GJ	9.81	Ethanol from wheat	Department of Industry Innovation and Science Australia (2017)

* Usual home tariff price without subsidy: 0.29 AUD/kWh (Synergy, 2019).

- Hydrogen delivery through tube tankers was modelled by calculating the costs associated with the price of the truck, tube tankers, the required amount of diesel, and the driver's wage (US Department of Energy, 2012). The calculated cost was found to be 2.30 AUD/kg. This cost of hydrogen distribution was found to be very close to 2.24 AUD/kg, which was the estimate received from a local transportation and logistics company (Centurion Logistics & Transport Services, Personal communication, January 2018).

- All the cost values were inflated by 3% every year (Lawania and Biswas, 2016) until the end of the project life (e.g., 20 years for ethanol and 35 years for hydrogen). The discounted cash flow analysis was used to determine the present value of the future costs associated with fuel production using **Equation 6.4** (Lawania and Biswas, 2016). Life cycle cost per VKT of fuel was then calculated using a capital recovery (Lee et al., 2009) factor as shown in **Equations 6.5–6.7.**

$$Present\ value = \sum_{i=1}^{i=n} \frac{C \times (1 + IR)^i}{(1 + DR)^i} \tag{6.4}$$

$$AC = PV \times CRF \tag{6.5}$$

$$CRF = \frac{(1 + x)^n}{(1 + x)^n - 1} \tag{6.6}$$

$$Life\ cycle\ cost/VKT = \ (AC \div AF) \times FC + AV_{af} \tag{6.7}$$

Where, i =1 , 2 , 3 ..... n; year value till end of life of the project, C = Future cost (AUD), IR =Inflation rate (3%) and DR= Discount rate (7%) [26], $AC =$ Annualized cost, $x =$ Real discount rate of 3.88% calculated from IR and DR [27], $AF =$ Per unit fuel production annually, $FC =$ Fuel consumption per km, $AV_{af} =$ Additional vehicle cost per km for an alternative fuel compared to gasoline.

- The producer margin of locally produced liquid fuel (i.e., ethanol in this study) was considered to be 0.10 AUD/L (Department of Agriculture and Food Western Australia, 2006), which was around 10% of the production cost. A similar profit margin (i.e., 10% of production cost) was also assumed for hydrogen fuel.
- An excise rate of 26.21% for ethanol in Australia was incorporated in the analysis. It has been assumed that there would not be any excise on hydrogen as both the Australian federal government and WA state governments were ready to support the penetration of hydrogen in different settings within the country (Government of Western Australia, 2019b). A GST (goods and service tax) of 10%, however, was applied to both the fuels for base case analysis as it was usually added to fuel costs in Australia (United Petroleum, 2017).
- The cost of an ethanol-blended gasoline vehicle was assumed to be the same as for the gasoline vehicle (He, 2013; Shirk et al., 2017). Costs of AUD 44,037, 39,326 and 70,650 were calculated for BEV, PHEV, and hydrogen fuel cell vehicles, respectively, based on a study by Miotti et al. (Miotti et al., 2017). The price of the gasoline vehicle (i.e., AUD 26,709) was based on the market price in WA (Toyota, 2020). The additional vehicle cost for alternative fuel vehicles compared to the gasoline vehicle due to the changes in powertrain was considered to be paid upfront during the vehicle purchase and subjected to discounted cash flow analysis with the same inflation and discount rate as like fuel (NSW

Government, 2014). The life of a new passenger vehicle in WA was 10.23 years (Hoque et al., 2019a).

- For carbon reduction credits (**Equation 6.8**), an average value of 40 AUD/tonne of GHG emission was assumed based on Wang et al. (2019). The assumed value was consistent with the guidelines from the International Monetary Fund and the United States Environmental Protection Agency (Kember et al., 2014). The indicator net benefit was calculated based on the difference between the costs per km of using gasoline and an alternative fuel option.

$$CRC/VKT = (GHG_{gasoline} - GHG_{af}) * CP \quad (6.8)$$

Where, $CRC =$ carbon reduction credit in AUD, $GHG_{gasoline} =$ life cycle GHG emission ($kgCO_{2e}$) per VKT from gasoline, $GHG_{af} =$ life cycle GHG emission ($kgCO_2$) from alternative fuel per VKT, $CP =$ Carbon price for per kg GHG emission in AUD.

6.2.6 Determination of threshold value

The threshold value for each TBL indicator was incorporated into the framework to assess whether the sustainability performance measures had been met (Fatimah and Biswas, 2016). By considering the potential vulnerability of liquid fuel security and the current utilization level of alternative fuels, which is almost zero in the WA transport sector (Blackburn, 2014; Clean Energy Council, 2019; Climate Council, 2018), threshold values were determined in such a way so that it would be possible to incorporate and assess further improvement strategies by identifying social, economic, and environmental hotspots (Hoque et al., 2019b).

A 33% reduction in GHG emission was chosen for global warming potential (GWP), as this reduction was required in the transport sector during 2020–2030 to maintain Australia's Paris agreement commitment of reducing the GHS emissions to 26–28% below 2005 levels by 2030 (Climate Council, 2018). The minimum reduction target for EU countries is 35% (Zucaro et al., 2018). Due to having no specific targets regarding the future reduction in the use of fossil fuels in WA (Clean Energy Council, 2019), the threshold values of this TBL indicator for alternative fuels were obtained from other developed countries that experience similar socio-economic situations, for example, EU countries and the USA, as shown in **Table 6.3**. The median value of fossil fuel reduction associated with the use of ethanol, electric vehicles, and hydrogen in passenger cars was found to be 34%. For water consumption (WC), the median values of WC for similar regions in terms of water stress and socioeconomics, such as the nine

European countries including UK, Italy, and Germany, and almost half of the USA (Table 6.3) that maintain standard practices during the production and use of alternative fuels, were considered for ascertaining the threshold value. Similarly, for land use (LU), alike regions in terms of land availability, such as Canada and the USA, were chosen to develop the threshold values.

Table 6.3: Threshold values for TBL indicators

Indicators	Thresholds	Source of Information	Description
GWP	Reduction ≥ 33%	Climate Council, Australia (Climate Council, 2018)	Alternative fuels should reduce at least 33% of GWP impact compared to gasoline in Australia.
FFD	Reduction ≥34%	Studies from regions socio-economically similar to WA (Evangelisti et al., 2017; Hawkins et al., 2013; Helmers et al., 2017; Lombardi et al., 2017; Mehmeti et al., 2018; Paul et al., 2016; Rapier, 2019; Sharma and Strezov, 2017; Tagliaferri et al., 2016).	At least a 34% FFD reduction is required to meet the criteria compared to base case gasoline.
WC	$\leq 1.48 \times 10^{-3}$ m^3/VKT	Studies from similar regions to WA in terms of water stress and socioeconomics (Elgowainy et al., 2016; Harto et al., 2010; Lombardi et al., 2017; Patyk et al., 2013).	Water consumption of alternative fuel cannot exceed 1.48×10^{-3} m^3/VKT
LU	$\leq 1.73 \times 10^{-6}$ ha.a/VKT	Studies from similar regions to WA in terms of land availability and socioeconomics (Helmers et al., 2017; Hoque et al., 2019a; Lombardi et al., 2017; Mehmeti et al., 2018; Pontau et al., 2015; Sharma and Strezov, 2017).	Land use of alternative fuels should be less than or equal to 1.73×10^{-6} ha.a/VKT
local job creation	$\geq 1.09 \times 10^{-3}$ man-hours/km	Rural Industries Research and Development Corporation, Australia (O'Connell et al., 2007)	The total job creation has to be $\geq 1.09 \times 10^{-3}$ man-hours/km.
CFF	$\geq 1.00 \times 10^{0}$ MJ/VKT	Median value of studies from regions socio-economically similar to WA (Evangelisti et al., 2017; Hawkins et al., 2013; Helmers et al., 2017; Lombardi et al., 2017; Mehmeti et al., 2018; Paul et al., 2016; Rapier, 2019; Sharma and Strezov, 2017; Tagliaferri et al., 2016).	Alternative fuels in WA should conserve equal to or more than 1.00×10^{0} MJ/VKT of fossil fuel.

OHAS	5 (100% agreement from the respondents)	Based on the methodology of Hoque et al. (Hoque et al., 2019b)	Acceptance levels were measured based on a 5-point Likert scale where 5 is the required level of acceptance.
HH_{VEE}	alternative fuel vehicle's emission < gasoline vehicle's emission	Rural Industries Research and Development Corporation, Australia (O'Connell et al., 2007)	One of the reasons for choosing alternative fuel is to reduce tail pipe emissions, which should be lower than the existing option (gasoline in this instance).
Life cycle cost	$\leq 8.13 \times 10^{-2}$ AUD/VKT	Rural Industries Research and Development Corporation, Australia (O'Connell et al., 2007)	The cost of alternative fuel should be compared with the existing option (gasoline in this study) to determine its financial viability.
CRC	$\geq 3.30 \times 10^{-3}$ AUD/km	Climate Council, Australia (Climate Council, 2018) and 40 AUD/tonne carbon price (Wang et al., 2019).	With the CRC of 40 AUD/tonne, the credit should be at least $3.30 \times 10{-}^{3}$ AUD/km based on the Climate Council of Australia.
Net benefit	Cost of using gasoline per VKT - Cost of using alternative fuel per VKT ≥ 0	Rural Industries Research and Development Corporation, Australia (O'Connell et al., 2007)	The cost of alternative fuel should be compared with the existing option (gasoline in this study) to determine its financial viability.

The indicator OHAS met the sustainability criteria when all the respondents scored 5 (i.e., 100%) (Hoque et al., 2019b; Lim and Biswas, 2017). Based on 40 AUD/tonne of GHG emission as the cost and a 33% GHG emission reduction target for Australia (Climate Council, 2018), a carbon reduction credit (CRC) of 3.30×10^{-3} AUD/km was selected as the minimum criterion for the alternative fuels to be sustainable. Job creation should increase due to the implementation of alternative fuels in a region (Garrett-Peltier, 2012). The threshold value for job creation (job creation $\geq 1.07 \times 10^{-3}$ man-hours/km) was considered for this study based on a research by Australian government (O'Connell et al., 2007). As vehicle assembly was considered to happen locally in WA, job creation potential through fuel life cycle and vehicle assembly was added to determine the threshold value. The cost of using gasoline (AUD/VKT) in WA was used as the threshold for the life cycle cost of alternative fuels (Daylan and Ciliz, 2016; Luo et al., 2009; O'Connell et al., 2007; Sengupta and Cohan, 2017; Shahraeeni et al., 2015; Zhou et al., 2017). Similarly, the difference between the costs of using gasoline and alternative fuel per VKT was used as the threshold for the net benefit indicator.

6.3 Interpretation of base case results

The base case results of the environmental and social life cycle assessments and the life cycle costing analysis are discussed in the forthcoming sections. In addition, a comparison of results with the threshold values has also been made to realize the sustainability performance.

6.3.1 Environmental life cycle assessment

The environmental life cycle assessment method as recommended in the International Organization for Standardization (ISO14040, 2006; ISO14044, 2006) was used to determine the environmental indicators for the study. The Australian indicators set allowed us to calculate all environmental indicators except for FFD. Besides, the CML method was used to calculate the FFD as it was recommended for Australia according to the Australian best practice life cycle impact assessment guideline (Renouf et al., 2015).

Table 6.4 shows the base case environmental results and the performance of different fuels based on threshold values. Hydrogen did not meet the environmental target (i.e., Threshold) mainly due to its high electricity requirements during the production stage. This high amount of electricity (54 kWh/kg of H_2) is alone found to be responsible for around 85%, 80%, 51% and 84% of total GWP, FFD, WC and LU impact respectively. . Ethanol feedstock production stage usually exhibits more than 80% environmental burden of total life cycle emission. E65 in this study, however, met the criteria in regard to GWP, FFD, and WC indicators because of its low resource requirements to grow ethanol feedstocks, especially cereal straw (53% contribution in the blend), which was a by-product of cereal production. E65, however, did not meet the land use criterion due to its land requirements to grow ethanol feedstocks. The farming of ethanol feedstocks (all three feedstocks in this study) in WA is rainfed, which reduces a large amount of the irrigation requirements compared to EU nations and the USA (Barton et al., 2014; Hoque et al., 2019a). Besides, around 60% of electricity in WA was produced from natural gas and renewable sources (Hoque et al., 2019a), which require less water than nuclear plants predominantly used in EU nations and coal-based electricity used in Victoria and New South Wales (Mekonnen et al., 2015). BEV and PHEV also met the criterion for WC because of their low requirements for water to generate electricity in WA. BEV failed to meet the GWP threshold (i.e., 29% lower than gasoline, as it needs to reduce a further 4% to meet the criterion). The electricity that was used for BEV charging was the main hotspot (1.21×10^{-1} kg CO_2/VKT) as it contributes 67% of the total GWP. The reason for PHEV having a higher impact than BEV in the GWP and FFD indicators was the phased use of gasoline (i.e., PHEV used 50% electricity and 50% gasoline in WA (Hoque et al., 2019a) as local electricity was found to use cleaner fuel than gasoline. As a result, PHEV failed to meet the GWP and FFD criteria. The combustion of gasoline (44%) and the use of electricity (31%) during the vehicle use stage were the main hotspots for the GHG emission. The usage phase, which consumes fuel (gasoline use: 49% FFD and electricity use: 31% FFD), was also the main reason for higher FFD emissions for PHEV.

Table 6.4: Environmental performances of different alternative fuel options

Indicators	Options	Calculated Results	Threshold	Remarks
GWP	Hydrogen	5.57×10^{-1} CO_2/VKT	33% lower than gasoline	120.00% higher than gasoline; fails to meet the criterion
	E65	1.49×10^{-1} CO_2/VKT		41.03% lower than gasoline; meets the criterion
	BEV	1.80×10^{-1} CO_2/VKT		28.92% lower than gasoline; fails to meet the criterion
	PHEV	2.17×10^{-1} CO_2/VKT		14.10% lower than gasoline fails to meet the criterion
FFD	Hydrogen	5.34 MJ/VKT	34% lower than gasoline	83% higher than gasoline; fails to meet the criterion
	E65	1.74 MJ/VKT		40% lower than gasoline; meets the criterion
	BEV	1.77 MJ/VKT		39.40% lower than gasoline; meets the criterion
	PHEV	2 MJ/VKT		31.36% lower than gasoline, fails to meet the criterion
WC	Hydrogen	1.49×10^{-3} m^3/VKT	$\leq 1.48 \times 10^{-3}$ m^3/VKT	Fails to meet the criterion
	E65	1.12×10^{-3} m^3/VKT		meets the criterion
	BEV	4.89×10^{-4} m^3/VKT		meets the criterion
	PHEV	5.35×10^{-4} m^3/VKT		meets the criterion
LU	Hydrogen	2.83×10^{-6} ha.a/VKT	$\leq 1.73 \times 10^{-6}$ ha.a/VKT	Fails to meet the criterion
	E65	5.72×10^{-6} ha.a/VKT		Fails to meet the criterion
	BEV	1.07×10^{-6} ha.a/VKT		meets the criterion
	PHEV	6.23×10^{-7} ha.a/VKT		meets the criterion

6.3.2 Social life cycle assessment

Social performances of alternative fuels are shown in **Table 6.5**. Ethanol was found to be the best-performing fuel with regards to job creation due to having labour-intensive upstream activities including farming, feedstock processing, and ethanol production. **Figure 6.1** shows

Table 6.5: Social performances of different alternative fuel options

Indicators	Options	Results	Threshold	Remarks
local job creation	Hydrogen	1.19×10^{-3} man-hours/VKT	$\geq 1.09 \times 10^{-3}$ man-hours/km	Meets the criterion
	E65	1.13×10^{-3} man-hours/VKT		Meets the criterion
	BEV	1.07×10^{-3} man-hours/VKT		Fails to meet the criterion
	PHEV	1.06×10^{-3} man-hours/VKT		Fails to meet the criterion
CFF	Hydrogen	-2.43×10^{0} MJ/VKT	$\geq 1.00 \times 10^{0}$ MJ/VKT	Fails to meet the criterion
	E65	1.17×10^{0} MJ/VKT		Meets the criterion
	BEV	1.15×10^{0} MJ/VKT		Meets the criterion
	PHEV	9.1×10^{-1} MJ/VKT		Fails to meet the criterion
OHAS	Hydrogen	5	5	Meets the criterion
	E65	5		Meets the criterion
	BEV	5		Meets the criterion
	PHEV	5		Meets the criterion
HH_{VEE}	Hydrogen	There is no tail pipe CO, PM, or NO_x emission		Meets the criterion
	E65	$CO \approx 1.77 \times 10^{-1}$ gm/VKT	2.75×10^{-1} gm/VKT	Lower than gasolinemeets the criterion
		$NO_x \approx 3.57 \times 10^{-3}$ gm/VKT	2.00×10^{-3} gm/VKT	Higher than gasoline fails to meet the criterion
		$PM \approx 6.58 \times 10^{-4}$ gm/VKT	1.85×10^{-3} gm/VKT	Lower than gasoline; meets the criterion
	BEV	There is no tail pipe CO, PM, or NO_x emission	Same threshold as like E65	Meets the criterion
	PHEV*	At least a 50% reduction of tail pipe CO, PM, and NO_x emissions compared to gasoline	Same threshold as like E65	Meets the criterion
				Meets the criterion
				Meets the criterion

* Electricity is used during 50% of the travel time. The fuel consumption of PHEV (0.04 L/km) is also lower than gasoline (0.06 L/km) during battery sustaining mode. Therefore, CO, PM, and NO_x reduction could be at least 50% compared with gasoline.

that around 60% of the jobs could be created (1.35×10^{-3} man-hours/L ethanol) during the conversion of feedstocks to ethanol and the remaining 40% were created from establishment (1.26×10^{-4} man-hours/L ethanol), harvest (4.49×10^{-4} man-hours/L ethanol), post-harvest management (4.46×10^{-5} man-hours/L ethanol), wood transportation to the plant (2.32×10^{-4}

man-hours/L ethanol), and ethanol transportation to the blending station (5.39×10^{-5} man-hours/L ethanol). Job creation potential for E65 in this study (1.13×10^{-3} man-hours/VKT) is, however, 4.2% lower than hydrogen due to the 65% replacement of imported gasoline in WA. Generating the electricity that is required for hydrogen production and storage (1.04×10^{-4} man-hours/VKT) and the hydrogen production plant (4.48×10^{-5} man-hours/VKT) were the two main job creation avenues for hydrogen fuel. Additionally, 1.15×10^{-7} job man-hours can be created from the water desalination that is required to supply water to the hydrogen production plant. Moreover, 1.042×10^{-3} man-hours working opportunity per VKT can also be created locally by the vehicle assembly plant for all fuel options. BEV failed to meet the criterion in terms of job creation by a small margin due to less labour-intensive electricity for charging. The PHEV also failed to meet the criterion for local job creation mainly due to the use of imported gasoline replacing 50% of the locally generated electricity.

All the fuel options were found to meet the OHAS threshold. In total, 144 responses in terms of OHAS were collected from the stakeholders of the supply chains for the four alternative fuels (i.e., 36 responses for each fuel). All the respondents for E65 provided 100% satisfaction (i.e., 5) and explained that the farming and conversion of feedstock to ethanol were safer than the production of gasoline. In the United States, for example, the worker fatality rate in oil and gas industries (2007 to 2016) was six times higher than the industry average (Allison and Mandler, 2018). Contact with equipment, exposure to harmful environments such as silica, fires and explosions, and falls from elevated areas are some of the possible fatal events reported in the oil and gas industry, though significant improvements have already been achieved in many areas (Allison and Mandler, 2018). Like E65, BEV and PHEV also met the OHAS threshold. For the usage stage of the BEV life cycle, two of the respondents recommended improvements in the battery cooling system to improve the battery performance during hot summer days, enabling the prevention of quicker degradation of the battery, but they still provided the required safety score. Research has shown that there are some concerns about the safety of electric vehicles batteries from fire due to some recent fire events, although it is unclear if the fire susceptibility of the vehicle is due to the electric vehicles battery issues (Jansen et al., 2019; Kong et al., 2018). The results from the EU Everyday Safety Project (EVERSAFE) revealed that the safety of electric vehicles was quite high and almost close to the levels of conventional vehicles (Bisschop et al., 2019). Electric vehicle manufacturers, however, have acknowledged the issue and have significantly improved the battery safety through the revision of charging, battery management systems (BMSs), thermal management, and mechanical crash protection (Bisschop et al., 2019). Additionally, “cut loop” systems that deactivate all the high-voltage connections during emergencies have also been incorporated into electric vehicles (Jansen et al., 2019). More development pertaining to battery safety (e.g., non-flammable electrolytes, better thermal management, innovative BMSs, integrated fire extinguishing capability, etc.) is also being researched for the next generation of batteries (Bisschop et al., 2019; Jansen et al., 2019; Kong et al., 2018).

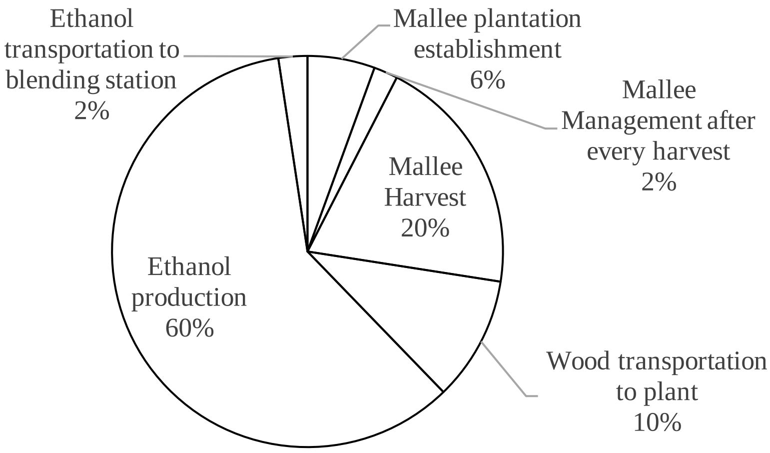

Figure 6.1: Job creation for 1 L ethanol supply to terminal gate from mallee.

There is some fear regarding the safety of hydrogen vehicles across Australia. Hydrogen is a highly inflammable gas that is stored in a high-pressure tank inside the vehicle (Hydrogen Strategy Group, 2018). This safety fear is mainly due to people’s unfamiliarity with hydrogen fuel, unlike gasoline (DSDMIP Queensland, 2019). Hydrogen has been used for oil refining and fertilizer production for many decades with an exemplary safety record (DSDMIP Queensland, 2019). All the respondents for hydrogen fuel were 100% satisfied with the safety procedures. Furthermore, there are examples showing that hydrogen is already suitably implemented as a transport fuel in several countries with the execution of safety protocols (COAG Energy Council Hydrogen Working Group, 2019). There are already millions of hydrogen vehicles on the roads in the USA, Japan, South Korea, and China (COAG Energy Council Hydrogen Working Group, 2019). WA’s local governments are liaising with the federal government and the countries with hydrogen experiences to devise safety protocols for hydrogen production and use (Government of Western Australia, 2019b). Sørensen (2012) found that the occupational health and safety scores with respect to death, severe injury, and stress/inconvenience during driving were the same for both HFCVs and gasoline vehicles.

Government campaigns, demonstration projects, promotional activities, and training are required to increase awareness among the community (DSDMIP Queensland, 2019; Hydrogen Strategy Group, 2018). Three hydrogen buses were included in the WA public transport service trial during the years 2004 to 2007. There were no health and safety issues reported during this trial. People were familiarized with hydrogen, and public acceptance of hydrogen use was increased after the trial (Government of Western Australia, 2008). Conservation of fossil fuels, on the other hand, was found to be negative for hydrogen fuel (−2.42 MJ/VKT) due to the large amount of energy required during its production stage. Similarly, PHEV also failed to meet the criteria for conservation of fossil fuel, amounting to 0.9 MJ/VKT, due to the use of gasoline during 50% of the travel time as mentioned earlier.

There are no tailpipe CO, PM, or NO_x emissions from BEV and HFCV, which fulfils the social sustainability objective of HH_{VEE}. PHEV also met the threshold in regard to HH_{VEE} by reducing the gasoline consumption through the use of electricity during 50% (base case scenario) of its travel time. Different results related to emissions from ethanol-blended gasoline were found in the literature, which was mainly due to differences in the test procedures, vehicle models, and engine parameters. Secondly, most of these studies did not investigate the complete fuel range from E0 to E85. Due to these reasons, the data used in this study were taken from a recent investigation conducted by Jin et al. (2017) for a passenger car, which took into account the complete fuel range and all possible emissions for fair comparison. Moreover, engines were also calibrated to match the different ethanol blends from E0 to E85 during the test. The test vehicle was also comprised of a three-way catalytic converter as an after-treatment device like existing gasoline cars on the road. NO_x emissions for E65 failed to meet the criterion as NO_x was found to increase compared to gasoline. Further investigations are, however, required regarding the NO_x emission, as both increasing and decreasing trends of NO_x relative to gasoline have been found in the literature when the percentage of ethanol is increased in the gasoline-ethanol blend (Jin et al., 2017; Masum et al., 2013).

6.3.3 Life cycle costing

Life cycle costs of E65, BEV, PHEV, and hydrogen and their comparisons with gasoline are shown in **Figure 6.2**. Based on the current scenario, E65 fuel was found to be the best option (0.096 AUD/VKT) but was still 1.5 cents higher than gasoline per VKT due to the higher fuel consumption of E65 compared to gasoline. There was no additional cost for E65 from the vehicle as the costs of both gasoline and E65 were assumed to be similar (He, 2013). The costs of ethanol production from wheat, cereal straw, and mallee wood were around 0.71, 1.01, and 1.10 AUD/L, respectively, without the producer profit margin. The findings of this study were similar to a previous study, which found that the ethanol production from wheat and wood could be around 0.70 AUD/L and 1.07 AUD/L, respectively, in Australia (AECOM Australia, 2016). The fuel costs for BEV and PHEV were even lower than that of gasoline mainly due to the availability of subsidized electricity tariffs for electric vehicle (BEV and PHEV) owners in WA. After the inclusion of additional vehicle cost, however, the life cycle costs of BEV and PHEV were estimated to be 0.22 and 0.18 AUD/VKT, respectively.

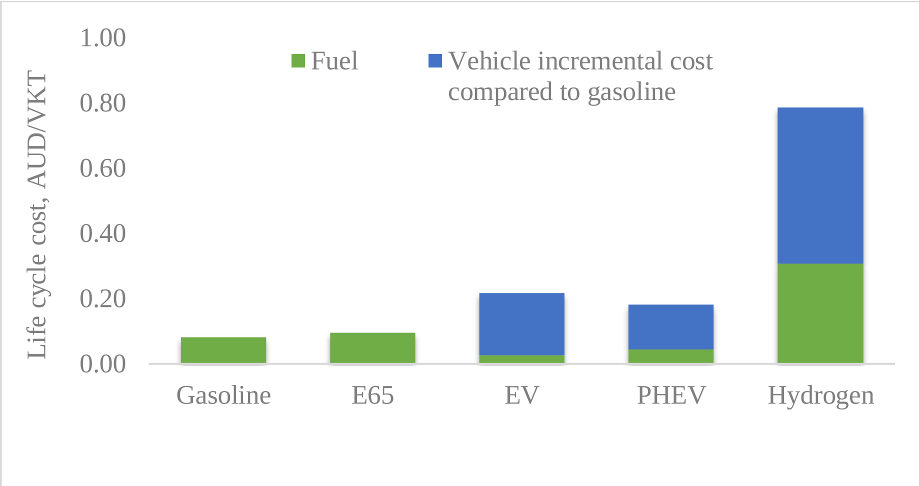

Figure 6.2: Life cycle costs of different fuel options.

Hydrogen, on the other hand, was the worst-performing fuel with regards to the life cycle cost indicator, being around 9.5 times higher than gasoline. The base case hydrogen fuel cost for this study was calculated as 31 AUD/kg (i.e., 0.31 AUD/VKT), compared with around 21 AUD/kg in refueling stations in the USA (D'Allegro, 2019). This higher cost in WA was expected due to the 30% higher manufacturing cost in Australia compared to the USA (Elaine, 2014). The electricity required (54 kWh/kg H_2) during the production of hydrogen was the main contributor (82%) to its cost. Other than this, around 12.4% of the cost was from the distribution of hydrogen.

None of the fuels met the economic sustainability criteria as they failed to compete with gasoline. The fuel option E65, however, met the criterion with regard to CRC. The low levels of fertilizers and resources required to grow the ethanol feedstocks were the main reason for attaining a higher carbon reduction credit for the use of E65 in WA. As shown in **Table 6.6**, all the fuel options also failed to meet the criterion for net benefit, even after the incorporation of carbon reduction credits.

Table 6.6: Performances of different alternative fuel options in terms of carbon reduction credit (CRC) and net benefit indicators.

Indicators	Options	Results, AUD/VKT	Threshold	Remarks
CRC	Hydrogen	-1.21×10^{-2}	$\geq 3.30 \times 10^{-3}$ AUD/VKT	Fails to meet the criterion
	E65	4.22×10^{-3}		Meets the criterion
	BEV	2.94×10^{-3}		Fails to meet the criterion
	PHEV	1.43×10^{-3}		Fails to meet the criterion
Net benefit	Hydrogen	Without CRC -7.06×10^{-1}	≥ 0 without CRC	Fails to meet the criterion
		With CRC -7.18×10^{-1}		Fails to meet the criterion
	E65	Without CRC -1.51×10^{-2}		Fails to meet the criterion
		With CRC -1.08×10^{-2}		Fails to meet the criterion
	BEV	Without CRC -1.36×10^{-1}		Fails to meet the criterion
		With CRC -1.33×10^{-1}		Fails to meet the criterion
	PHEV	Without CRC -1.00×10^{-1}		Fails to meet the criterion
		With CRC -9.87×10^{-2}		Fails to meet the criterion

6.4 Improvement strategies

Improvement strategies related to TBL sustainability were incorporated into the framework in such a way as to make them applicable in the near future in WA. Improvement strategies have been suggested in the impending sections when any indicators failed to meet the required sustainability objectives. Following the interdependencies in the framework, revised ELCA, SLCA, and LCC results are also presented.

6.4.1 Environmental strategies

Hydrogen fuel did not meet the threshold of any environmental indicators. Therefore, a "hotspot" analysis was conducted based on the LCA results. This helped to identify and incorporate improvement strategies to be able to achieve the required level of environmental performance. The electricity consumption during the production of hydrogen was found to be the main environmental hotspot during the life cycle of hydrogen. Electricity generation from clean energy sources, such as renewables, was considered to treat the hotspot. WA has huge potential to produce most of its electricity (90% to 100%) from wind and solar (Laslett et al., 2017; Lu et al., 2017). The Perth desalination plant in WA, for example, uses wind-generated electricity from the 80 MW Emu Downs Wind Farm (Water Technology, 2019). Based on WA's future renewable hydrogen production strategy (Government of Western Australia, 2019b), a scenario with a combination of wind and solar energy (50% wind and 50% solar) was considered for electricity generation for hydrogen production. After incorporating the strategy into the framework, as shown in **Table 6.7**, all the environmental criteria were found to be met when compared to the threshold values. The calculations related to the improvement strategies are summarized in **Appendix-E**.

BEV failed to meet the criteria with regard to the GWP indicator, and the electricity required for charging the battery was identified as the main hotspot. As described in chapter 4, there could be around 37% renewable energy in the WA electricity mix in the next 10 years according to the renewable energy penetration forecast (The Climate Institute, 2009). This cleaner electricity production strategy could potentially be able to meet all the criteria for BEV. In the case of PHEV, three possible strategies, namely, E10 as a replacement for gasoline, cleaner electricity for charging (as used for the BEV), and a solar rooftop photovoltaic panel (180 W_p) equipped with the vehicle, were considered to treat the hotspots. E10 was proposed as no vehicle modification was required due to this fuel change (O'Connell et al., 2007). The 180 W_p solar cell was proposed as this had already been applied in the Toyota Prius Prime in Japan without causing any inconvenience to users (Dujmovic, 2019) and WA has an enormous solar radiation potential to charge electric vehicles with integrated solar systems (Geoscience Australia and BREE, 2014). The average solar irradiation in WA was considered to be 5.30 kWh/m^2.day (Australian Bureau of Meteorology, 2019) to calculate the electricity generated by photovoltaic cells. The car was assumed to be exposed to the sun for at least for 2.5 h/day, which is realistic given the long sunshine hours (7.92 h/day) in WA (Australian Bureau of Meteorology, 2019). The efficiency of the photovoltaic system was assumed to be 14% due to its low cost like rooftop photovoltaic (PV) panels (Hoque and Kumar, 2013).

E65 failed to meet the land use criterion due to the use of large amounts of land for wheat feedstock production. Of these feedstocks, grain contributing 10% of the blend (i.e., 10% ethanol from wheat) is responsible for utilizing 71% of land (5.29×10^{-4} ha.a/L), while straw contributing 53% of the blend occupies only 19% of the land (2.67×10^{-5} ha.a/L). The land use for mallee-based ethanol (3.56×10^{-4} ha.a/L) was not significant due to the small portion (2%) of ethanol in the blend. In WA, the yield of rainfed cereal (especially wheat, which accounts for 70% of cereal production) mainly depends on the amount of rainfall (Hochman and Horan, 2018; Robertson et al., 2016). Research studies and investigations suggest that a yield gap of 3 tonne/ha (Hochman and Horan, 2018) in WA's water-stressed wheat belt can be mitigated through different improvement strategies, such as genetic improvement, utilization of nitrogen input as required, application of bio-mineral fertilizer, prevention of damage to the grains from frost and heat by timely sowing, soil surface and residue management, crop rotation, and integrated weed control (Assainar et al., 2020; Barton et al., 2016; Hochman and Horan, 2018; Robertson et al., 2016). Yield improvement with the aforementioned strategies, however, was found to be uncertain due to the potential cost and benefit constraints in large-scale grain production (Robertson et al., 2016). The land use impact of E65 was found to be still 2 times higher than the threshold, even after the cereal yield in WA was increased from 1.9 tonnes/ha (base case) to 4.9 tonnes/ha by overcoming the yield gap of 3 tonne/ha. The E55 blend (E2 from mallee and E53 from cereal straw), however, met all other environmental criteria. It has been found that farmers are willing to plant more mallee trees in WA if there is a demand for it (URS Asutralia, 2008). Therefore, it could be possible to produce an environmentally sustainable ethanol blend of more than E55 in the future in WA by utilizing a mix of mallee and straw. There could be sustainability issues from the land use impact again due to the increase of mallee in the ethanol blend. This issue, however, can be alleviated if marginal and under-utilized land, such as the narrow belt around the current agricultural field, is utilized for biofuel feedstock production (Kelly, 2015; Pontau et al., 2015; RIRDC, 2009).

Table 6.7: Strategies to improve the environmental sustainability performances

Options	Strategies	Effect on Sustainability Performance
Hydrogen	Renewable electricity (wind and solar) (Biswas et al., 2013; Hoque et al., 2019a)	GWP: 69.37% < gasoline; FFD: 65.28% < gasoline WC: 3.55×10^{-4} m^3/km; LU: 1.64×10^{-7} ha.a/km
BEV	Cleaner electricity for charging (Hoque et al., 2019a)	GWP: 49.86% < gasoline; FFD: 49.70% < gasoline WC: 4.80×10^{-4} m^3/km; LU: 1.07×10^{-6} ha.a/km
PHEV	Use of E10 in place of gasoline (Hoque et al., 2019a) Cleaner electricity for charging (Hoque et al., 2019a) 180 W_p solar cells installed on the car (Dujmovic, 2019)	GWP: 34.70% < gasoline; FFD: 43.57% < gasoline WC: 5.27×10^{-4} m^3/km; LU: 6.67×10^{-7} ha.a/km
Ethanol	Ethanol blend E55 considered in place of E65	GWP: 34.51% < gasoline; FFD: 34.01% < gasoline WC: 1.06×10^{-3} m^3/km; LU: 1.69×10^{-6} ha.a/km

6.4.2 Social strategies

All fuel scenarios that are found to be environmentally friendly are considered for social assessment. Any social changes that take place due to the environmental improvement strategies are taken into account in the following SLCA (**Table 6.8**). Job creation potential decreased by 1.12% due to the replacement of E65 with E55. This was because of the reduction in labour-intensive ethanol in the blend. The job creation potential for hydrogen, BEV, and PHEV, however, increased by around 20%, 3%, and 4%, respectively, from the base case after incorporating the environmental strategies, such as renewable electricity, E10 in place of gasoline, etc. The increase in net jobs with the uptake of renewable-based electricity was similar to the findings of the Climate Council of Australia (Climate Council, 2016).

The PHEV still failed to meet the threshold value in regard to job creation potential even though Western Australia holds substantial reserves of all the required minerals for battery production for PHEV to further increase jobs (Commonwealth of Australia, 2018). Two world famous lithium processing companies, Tianqi and Albemarle, are already investing in WA for lithium processing. Three lithium processing plants were in the development phase in 2019 (Commonwealth of Australia, 2018). With its unique advantages and the growth of the electric vehicles all over the world, the WA state government has already investigated the value chain of the battery industry and is currently examining the opportunity more closely in conjunction with the federal government in order to become the world leader in the sustainable battery industry (Government of Western Australia, 2019a). Three locations, Kwinana, Kalgoorlie, and Bunbury had already been selected as suitable locations (Commonwealth of Australia, 2018). If the batteries were considered to be produced locally in WA, the job creation potential for BEV and PHEV was increased to 1.19×10^{-3} man-hours/VKT and 1.10×10^{-3} man-hours/VKT, respectively. The PHEV met the threshold value after incorporating this strategy into the framework. The increase in job creation with this approach for hydrogen was found to be quite small (1.84×10^{-10} man-hours/VKT) due to the small battery capacity (only 1.6 kWh) compared to BEV and PHEV. The indicator CFF was also increased for all the fuel options except E55 after incorporating the environmental strategies. The CFF was found to decrease with E55 mainly due to the increase of gasoline in the blend compared to E65, but it still met the sustainability criterion.

The incorporated environmental strategies were not found to affect the OHAS consensus. Respondents in the electricity generating stage, for example, were consulted again regarding cleaner electricity production (environmental strategy for BEV, PHEV, and hydrogen) in WA to further improve the OHAS. The respondents indicated that the OHAS would slightly increase from the base case due to the replacement of fossil fuel-based electricity. The reason for this was the reduction of the upstream fuel extraction phase (i.e., mining of coal/oil/gas). Furthermore, renewable electricity production through wind and solar reduces the risk of accidents and hazardous environments compared to thermal power plants. Similarly, OHAS for E55 also remained the same as E65 because both of these fuel options required the same supply chain during the production and use stages (i.e., using the same vehicle).

The fuel option E55 also did not meet the NO_x emission reduction target. Other studies suggest that the NO_x emission could increase or decrease with higher ethanol blends (Doğan et al., 2017; Jin et al., 2017; Karavalakis et al., 2012; Karavalakis et al., 2014; Masum et al., 2013; Oh and Cha, 2015). It can reduce by up to 30% or increase by 93% due to the replacement of gasoline with E55 (Jin et al., 2017; Karavalakis et al., 2012; Karavalakis et al., 2014; Masum et al., 2013). This is mainly due to the inter-vehicle variability and test procedures (Delavarrafiee and Frey, 2018; Masum et al., 2013). These results clearly indicate that the reduction of NO_x with the higher ethanol blend is not consistent. For addressing this sustainability issue, the following strategies have been recommended (Jin et al., 2017; Karavalakis et al., 2012):

- Sophisticated engine calibration: Previous studies explain that the higher ethanol blends lean out the air-fuel mixture, which results in an increase in NO_x emission (Karavalakis et al., 2012). Thus, the engine control module of the vehicle needs to be able to adjust the air–fuel ratio with the amount of ethanol content in the blend (Karavalakis et al., 2012).
- After-treatment devices: The use of exhaust gas recirculation (EGR) as an after-treatment device can also help to meet the vehicle exhaust emission standard (Fischer et al., 2017; Wei et al., 2012). It has been found that clean and cooled EGR in the gasoline engine with the aid of gasoline particulate filters (GPFs) could reduce HC, CO, NO_x, and PM without compromising fuel economy (Fischer et al., 2017). The cooled clean EGR technique decreases knocking, which enables a higher compression ratio for fuel economy although some engine power is required for cooling (Fischer et al., 2017).

The social strategy regarding the local production of batteries for job creation potential also changes the environmental performances and social indicators, such as CFF, due to the interdependencies of these sustainability objectives. These relative changes, however, do not affect the sustainability decision-making process as further environmental burdens could be reduced due to avoidance of the transport of batteries from overseas. The potential reductions in transportation in terms of tonne-kilometres (tkm) for BEV, PHEV, and hydrogen were 2.76×10^{-2} tkm/VKT, 8.75×10^{-3} tkm/VKT, and 1.67×10^{-3} tkm/VKT, respectively, for this strategy.

Table 6.8: Revised environmental and social performances of alternative fuels.

Options	Social Performance after Incorporating Environmental Strategies	Revised Results after Incorporating Social Strategies	
		Environmental	Social
Hydrogen	local job creation: 1.43×10^{-3} man-hours/VKT CFF: 1.90×10^{0} MJ/VKT OHAS: 5 HH_{VEE}: Same as base case	GWP: 69.38% < gasoline FFD: 65.30% < gasoline WC: 3.55×10^{-4} m^3/km LU: 1.64×10^{-7} ha.a/km	local job creation: 1.43×10^{-3} man-hours/VKT CFF:1.91×10^{0} MJ/VKT OHAS: 5 HH_{VEE}: Same as base case
BEV	local job creation: 1.10×10^{-3} man-hours/VKT CFF: 1.45×10^{0} MJ/VKT OHAS: 5 HH_{VEE}: Same as base case	GWP: 50.10% < gasoline FFD: 50.04% < gasoline WC: 4.78×10^{-4} m^3/km LU: 1.07×10^{-6} ha.a/km	local job creation: 1.19×10^{-3} man-hours/VKT CFF: 1.46×10^{0} MJ/VKT OHAS: 5 HH_{VEE}: Same as base case
PHEV	local job creation: 1.07×10^{-3} man-hours/VKT CFF: 1.31×10^{0} MJ/VKT OHAS: 5 HH_{VEE}: Further reduction * of tail pipe emission. Minimum reduction could be around 56.6% compared to gasoline.	GWP: 34.78% < gasoline FFD: 43.68% < gasoline WC: 5.26×10^{-4} m^3/km LU: 6.67×10^{-7} ha.a/km	local job creation: 1.10×10^{-3} man-hours/VKT CFF: 1.31×10^{0} MJ/VKT OHAS: 5 HH_{VEE}: Social strategies have no effect on exhaust emission.
Ethanol (E55)	local job creation: 1.11×10^{-3} man-hours/VKT CFF: 1.00×10^{0} MJ/VKT OHAS: 5 HH_{VEE}: CO ≈ 1.92×10^{-1} gm/VKT; PM ≈ 8.18×10^{-4} gm/VKT; NO_x emission (3.86×10^{-3} gm/km) still fails to meet the criterion due to the higher value compared to gasoline per km.	GWP: 35.61% < gasoline FFD: 34% < gasoline WC: 1.07×10^{-3} m^3/km LU: 1.72×10^{-6} ha.a/km	local job creation: 1.11×10^{-3} man-hours/VKT CFF: 1.00×10^{0} MJ/VKT OHAS: 5 HH_{VEE}: To make this criterion sustainable, further engine calibration and/or after-treatment devices are required for the consistent reduction of NO_x compared to gasoline.

* Electricity was used during 56.6% of the travel time after implementing the strategies (it was 50% in the base case).

The revised environmental and social performances are shown in Table 6.8. No further environmental changes are considered for the minor change in engine calibration for E55 fuel due to its minimal effect on life cycle emissions. A slight increase in fuel consumption (around 2%) was, however, considered based on a study by Wei et al. (Wei et al., 2012) due to the after-treatment techniques to control NO_x. After incorporating this into the framework, the fuel option E55 failed to meet the FFD and CFF indicators. Based on the hotspots in ethanol production, one more additional strategy was considered through the use of renewable electricity for enzyme production (Hoque et al., 2019a) in order to satisfy all the social sustainability criteria.

6.4.3 Economic strategies

The costs associated with environmentally and socially sustainable scenarios (Table 6.8) are incorporated into the framework**.** The recalculated cost for E55 (0.102 AUD/VKT) was around 2.1 cents higher than the threshold (0.081 AUD/km). The cost increased slightly after switching to E55 due to the replacement of cheap wheat-based ethanol with costly lignocellulosic ethanol in the blend. Plant cost was identified as one of the economic hotspots during ethanol production. The fuel option E55 met the threshold value in regard to all economic indicators after incorporating the following three strategies:

- Long-term soft loan for the capital cost at the rate of 3% interest rate over the project life.
- Renewable energy projects received capital subsidy in Australia (Department of Agriculture and Food Western Australia, 2006). It has been proposed that 10% of the capital cost (around AUD 19.5 M) of the ethanol project would be funded by the government grant (Asustralian Renewable Energy Agency, Personal communication, January 2020).
- Removal of excise rate on ethanol (Department of Agriculture and Food Western Australia, 2006) and GST on E55, which would reduce 10% of the fuel cost for the end consumer (Parliament of Australia, 2020).

The economic hotspot for hydrogen fuel was due to the large amount of electricity consumption during its production. Oxygen that was produced from the hydrogen plant as a by-product was utilized as an economic improvement strategy to increase the revenue. This O_2 can be used locally in aquaculture, waste treatment plants, and industrial furnaces (Bruce et al., 2018; Kato et al., 2005). Around 5% of the hydrogen production plant cost was eliminated with this strategy (Harvego et al., 2012; Kato et al., 2005). Solar and wind-based electricity was used as an improvement strategy, as shown in Section 6.4.1, to satisfy the environmental criteria. As indicated in a study by Bruce et al. (2018), wind and solar-based low-carbon renewable electricity for hydrogen production plants could be possible in Australia, as shown in **Table 6.9**.

For the continuous production of hydrogen, option 1 from Table 6.9 was considered for this study due to its high capacity factor. Additionally, the hydrogen plant can gain competitive advantages by using option 3 when it is available. With a 10% capital subsidy, a soft loan scheme of 3% over the life of the project, as well as the removal of GST and the utilization of the by-product oxygen, it was shown that the hydrogen fuel cost was similar to gasoline per VKT, provided that the hydrogen production plant received electricity at the rate of 8.3 cents/kWh. This assumption of electricity cost was also consistent with the latest wholesale electricity spot price in the Australian national electricity market (Australian Government, 2020). The estimated costs after the implementation of each strategy are provided in **Appendix-E**.

Table 6.9: Possible low-cost renewable electricity options for hydrogen production plants in Australia.

Options	Description	Expected cost (Bruce et al., 2018)
1	Hydrogen plants use electricity from the network, but low-emission electricity is still possible through power purchase agreements (PPAs). PPAs help buyers to secure low-priced renewable electricity from remote area power supply systems that are usually operated by wind and solar plants in Australia through long-term contracts (Energetics et al., 2018; WWF-Australia, 2016). The agreed price may vary up to a certain level based on the spot price in the national electricity market (Energetics et al., 2018).	Depending on the contract and government support, the average electricity price in Australia could be as low as 6 cents/kWh for generating electricity from renewable wind and solar.
2	Electricity is considered to be supplied from a renewable energy farm in the vicinity of hydrogen plants.	The estimated cost could be the same as option 1 (i.e., 6 cents/kWh).
3	Due to the increasing trend of renewable electricity, surplus renewable electricity from the grid will be available as "curtailed renewable energy" in the grid.	The price is estimated to be low (2 cents/kWh) for this curtailed electricity due to the low demand for this surplus electricity.

The strategy related to utilization of oxygen during hydrogen production as a by-product had interdependencies with environmental and social sustainability in the framework. This small amount of change, however, did not influence the ELCA and SLCA indicators significantly.

For example, less than 1% reduction was observed for the overall life cycle environmental emission. The electricity cost at the domestic user level was assumed to be the same, even after the penetration of 37% renewables into the grid as the base case (Mzengrab, 2019; Vorrath, 2020). Thus, the fuel cost of the BEV remained the same as the base case. After incorporating the environmental and social strategies, the fuel cost of the PHEV was, however, decreased from 0.043 AUD/VKT to 0.040 AUD/VKT due to the reduction of gasoline use per km.

The BEV, PHEV, and HFCV, however, did not meet any of the economic criteria due to their high vehicle cost. To meet all the economic criteria for BEV, PHEV, and HFCV, around 13.58, 9.67, and 48.05 cents/VKT of financial subsidies are still required. The subsidies are essential for a few years at the initial stages to enable market penetration (Arslan et al., 2010; Holtsmark and Skonhoft, 2014). For example, Norway was the first country that introduced incentives on electric and hybrid electric vehicle acquisition back in the 1990s, and the country is currently the world leader based on market share of electric vehicle sales (RAC, 2020). Germany, Sweden, France, China, and the USA are also among the most electric vehicle-using countries. The initial subsidies on electric vehicles provided by these countries were between AUD 5000 and AUD 16,000 in 2019 (Volkswagen AG, 2019). The following strategies in WA are expected to ease the penetration of BEV and PHEV:

- The removal of GST on vehicle purchases would provide savings of around AUD 4,000 on BEV and AUD 3,575 on PHEV.
- A fifty percent subsidy on vehicle registration can generate around AUD 4,000 benefit over the life of the vehicle. This subsidy comprises the license fee, recording fee, insurance duty, and GST but will not include insurance because injury cover is required for driver and passenger wellbeing (The Royal Automobile Club of WA, 2020).
- Currently, there is no import duty on passenger vehicles in Australia from some countries, including Japan and the USA, under the free trade agreement. Inclusion of an import duty of around 10% on gasoline vehicles can reduce the difference in cost between gasoline and alternative fuel vehicles to AUD 1,000.
- The remaining amount of around AUD 4,200 for BEV and AUD 1,100 for PHEV can be covered either by direct subsidy and/or tax benefits for the electric vehicle owner.
- Some in-kind benefits, such as access to bus lanes, priority parking in shopping centres, and reserved public parking locations, may popularize BEVs and PHEVs in WA (Climate Works, 2018; Electric vehicle Council Australia, 2019; Parliament of Victoria, 2018).

Hydrogen, on the other hand, was the more environmentally friendly transport fuel than electricity when hydrogen was produced by renewable electricity. After incorporating all the economic strategies, the hydrogen fuel cost was found to be similar to that of gasoline as well. Hydrogen as a transport fuel, however, may not be sustainable at this stage in WA due to the high vehicle cost. Supply chain improvement, mass production, and further research could bring the cost of HFCV close to gasoline in 2030 (Bruce et al., 2018). During the breakdown of cost, it appeared that just two components of HFCV (fuel cell and hydrogen tank) contribute around 70% of the cost of the vehicle (Miotti et al., 2017). More research and development on HFCV are required to reduce the cost of these two components. Constructing hydrogen infrastructure is another barrier to hydrogen-based transportation, which the WA government needs to build from scratch unlike electric vehicle infrastructure. To kick start hydrogen transportation in WA, hydrogen vehicles could be included in government's fleets and governments need to start establishing infrastructure, such as hydrogen refueling stations.

6.5 Summary results of the LCSA framework for Western Australian transport fuel

The LCSA framework has been used successfully to assess alternative transport fuels for Western Australia. The framework includes fuel selection; indicator selection according to local needs; data collection; ELCA, LCC, and SLCA assessments; determination of threshold values for sustainability decisions; and cleaner production strategies to achieve TBL sustainability. The framework enables an investigation into the base case sustainability implications of potential fuel options for the state and finding suitable strategies to meet the sustainability objectives. The framework reveals that three options, namely, ethanol-gasoline blend E55, BEV, and PHEV, would be sustainable in WA with the recommended cleaner production strategies and financial assistance, as shown in **Table 6.10**. Hydrogen fuel showed better environmental and social performance when hydrogen was produced from renewable energy. The hydrogen fuel option, however, was found to be unsustainable due to the high cost of HFCV.

The suggested strategies, for example, the production of alternative fuels with environmentally friendly cleaner alternatives, financial incentives for alternative fuel production and alternative vehicle purchase, etc., are common and have been incorporated in such a way so that their objectives are achievable in the near future locally in WA. For example, using renewable energy for hydrogen production and cleaner grid electricity (i.e., with 37% renewables) for BEV charging could help to meet all the environmental and social criteria for the fuels. The implementation of these strategies is viable in WA due to having a large amount of wind and solar energy potential (Climate Council, 2016; Government of Western Australia, 2019b). The strategy of local battery production is suggested for the PHEV to meet the local job creation criterion, as WA is in a unique position for sustainable battery production (Government of Western Australia, 2019a). The strategy of local battery production also helps other fuel options, especially BEV due to its larger battery, to generate more jobs locally in WA. Furthermore, the financial incentives that are already in place in several countries have been suggested for electric vehicles to make them economically competitive in relation to gasoline (Volkswagen AG, 2019). Similarly, economic support for biofuel production and use is also common in various countries in the world (IEA, 2016). Improvement strategies are determined in this study to materialize the basis of the framework as this could assist policymakers to implement alternative fuels in Western Australia. The framework is highly flexible as it allows fuel selection and accommodates scenario analysis to address the region-specific needs and preferences.

Table 6.10: Final outcome of Hoque et al.'s framework for transport fuel in Western Australia (WA)

Options	Base Case Sustainability Issues	Sustainability Improvement Strategies	Implications of Improvement Strategies			Final Status of Sustainability
			Environmental	Social	Economic	
Hydrogen+	Fails to meet all environmental, one social (CFF), and all economic indicators	• Renewable electricity (solar and wind) for hydrogen production • Utilization of oxygen by-product from hydrogen production plant • Soft loan for the plant capital cost (3% interest rate over the life of the project) • Electricity for the hydrogen production plant at the rate of 8.3 cents/kWh through PPA • Removal of GST on hydrogen purchase for the public user • No economic strategies were considered for HFCV due to its high cost	Meets all the criteria GWP: 69.38% < gasoline FFD: 65.30% < gasoline WC: 3.55×10^{-4} m^3/km LU: 1.64×10^{-7} ha.a/km	Meets all the criteria local job creation: 1.43×10^{-3} man-hours/VKT CFF: 1.91×10^{0} MJ/VKT OHAS: 5 HH_{VEE}: No tail pipe CO, PM, or NO_x emission	Fails to meet life cycle cost and net benefit criteria Life cycle cost: 5.62×10^{-1} AUD/VKT CRC: 7.02×10^{-3} AUD/VKT Net benefit without CRC: -4.80×10^{-1} AUD/VKT Net benefit with CRC: -4.73×10^{-1} AUD/VKT	Economic sustainability was not achieved due to the high cost of HFCV.
BEV	Fails to meet one environmental (GWP), one social (local job	• Cleaner electricity (grid with 37% renewable electricity) for charging BEV • The removal of GST on BEV purchase	Meets all the criteria GWP: 50.10% < gasoline	Meets all the criteria local job creation: 1.19×10^{-3} man-hours/VKT	Meets all the criteria Life cycle cost: 8.13×10^{-2} AUD/VKT	All three dimensions of sustainability were achieved.

	creation criteria), and all economic indicators.	• 50% subsidy on BEV registration • Inclusion of import duty on gasoline vehicle • Around 4200 AUD of direct subsidy and/or tax benefits for BEV owner	FFD: 50.04% < gasoline WC: 4.78×10^{-4} m^3/km LU: 1.07×10^{-6} ha.a/km	CFF: 1.46 MJ/VKT OHAS: 5 HH_{VEE}: No tail pipe CO, PM, or NO_x emission	CRC: 5.07×10^{-3} AUD/VKT Net benefit without CRC: 0.00×10^{0} AUD/VKT Net benefit with CRC: 5.07×10^{-3}AUD/VKT	
PHEV	Fails to meet two environmental (GWP and FFD), two socials (local job creation and CFF), and all economic indicators.	• Use of E10 in place of gasoline • Cleaner electricity for charging as with BEV • 180 Wp solar PV panel attached on the vehicle to reduce use of liquid fuel • Local production of battery in WA • The removal of GST on PHEV purchase • 50% subsidy on PHEV registration • Inclusion of import duty on gasoline vehicle • Around 1100 AUD direct subsidy and/or tax benefits for PHEV owner	Meets all the criteria GWP: 34.78% < gasoline FFD: 43.68% < gasoline WC: 5.26×10^{-4} m^3/km LU: 6.67×10^{-7} ha.a/km	Meets all the criteria local job creation: 1.10×10^{-3} man-hours/VKT CFF: 1.31×10^{0} MJ/VKT OHAS: 5 HH_{VEE}: Vehicle exhaust emission (CO, PM, and NO_x) lower than gasoline. Vehicle runs on electricity during 56.6% of its travel time after implementing the strategies.	Meets all the criteria Life cycle cost: 8.13×10^{-2} AUD/VKT CRC: 3.52×10^{-3} AUD/VKT Net benefit without CCR: 0.00×10^{0} AUD/VKT Net benefit with CCR: 3.52×10^{-3} AUD/VKT	All three dimensions of sustainability were achieved.

E65*	Fails to meet one environmental (land use), one social (HH_{VE}: NO_x emission for E65 was found to be higher than gasoline), and two economic (life cycle cost and net benefit) indicators.	• E55 to be considered in place of E65 by excluding land-intensive wheat-based ethanol • Renewable electricity for enzyme production • Engine control strategy and after-treatment device to reduce the NOx emission compared to gasoline • Soft loan (3% interest rate) for the capital cost over the period of project life • 10% subsidy on plant capital cost • Removal of excise duty on ethanol • Removal of GST on E65 for the user	Meets all the criteria GWP: 35.61% < gasoline FFD: 34.00% < gasoline WC: 1.07×10^{-3} m^3/km LU: 1.72×10^{-6} ha.a/km	Meets all the criteria local job creation: 1.11×10^{-3} man-hours/VKT CFF: 1.00×10^{0} MJ/VKT OHAS: 5 HH_{VEE}: Tail pipe CO and PM emissions are lower than gasoline. Consistent NO_x emission reduction compared to gasoline is also possible with engine control strategies and after-treatment devices.	Meets all the criteria Life cycle cost: 8.13×10^{-2} AUD/VKT CRC: 3.61×10^{-3} AUD/VKT Net benefit without CCR: 0.00×10^{0} AUD/VKT Net benefit with CCR: 3.61×10^{-3} AUD/VKT	E55 * meets all three dimensions of sustainability.

[+] Hydrogen fuel meets the OHAS indicators, but a standard safety protocol for hydrogen production and use needs to be devised. Moreover, training and a promotional campaign by the government are also required.

* Considering E55 in place of E65 to meet the environmental criteria. Further investigation is required regarding tail pipe NO_x emission when the vehicle runs on E55. Consistent reduction of NO_x compared to gasoline needs to be ascertained with the sophisticated engine control and after-treatment strategies as mentioned in the improvement strategy column to meet the human health criterion.

6.6 Conclusions

The LCSA framework has been practically implemented successfully for alternative transport fuels in WA. Four alternative energy sources, namely, ethanol (E65), hydrogen, electricity, and electricity-gasoline hybrid, were selected based on the availability of local resources. The framework reveals that none of the fuels are sustainable in the base case as all of them failed to meet the criteria for one or more TBL indicators. Ethanol E65 was unsuccessful in meeting the land use criterion due to the higher land requirement during the production of feedstock compared to other fuel options. BEV and PHEV failed to meet the GWP criterion by a margin of 4% and 19% when compared to the threshold value. Both the electric vehicle options also failed to meet the job creation indicator. Except for local job creation, human health, and OHAS, hydrogen fuel failed to meet the TBL indicators mainly due to the consumption of a large amount of electricity during the production of hydrogen.

The framework has been successful in incorporating cleaner production strategies and strengthening the inter-relationship between the three pillars of sustainability. Three improvement strategies, namely, use of E10 in place of gasoline, placement of 180 W_p solar PV panels on vehicles, and cleaner electricity for charging, were required to make the PHEV environmentally sustainable. Similarly, renewable energy for hydrogen production and cleaner electricity for BEV charging were considered for the hydrogen and BEV, respectively, to meet the sustainability thresholds in regard to environmental indicators. The fuel option E65 failed to meet the land use criterion. Thus, E55, which met all the environmental criteria, was proposed. After incorporating the environmental improvement strategies, the use of hydrogen as a fuel option was found to be the best-performing fuel in regard to the GWP. It resulted in around a 69% reduction in GWP and about a 65% reduction in the FFD indicator when compared to gasoline due to the replacement of current fossil-based electricity with wind and solar energy. The reductions of GHG emission for BEV and PHEV were found to be around 50% and 35%, respectively, after incorporating the strategies. For PHEV, local battery production was required to meet the job creation criterion. The strategy of local battery production was considered due to WA's anticipated leading role in sustainable battery production within 5 to 10 years. Research suggests that NO_x emissions from the vehicle exhaust might increase or remain similar compared to gasoline for a higher ethanol blend (E55 in this study). It is also recommended that engine control strategies and after-treatment devices are required to maintain a consistent NO_x reduction compared to gasoline during the use of a higher ethanol blend.

The life cycle cost of environmentally and socially sustainable E55, BEV, PHEV, and hydrogen fuels was found to be 0.10, 0.22, 0.18, and 0.79 AUD/VKT, respectively. For economic sustainability, E55 required a lesser subsidy (2.1 cents/VKT) compared to other fuel options. The fuel costs of BEV and PHEV were found to be 66% and 50% lower than gasoline per VKT due to the subsidized electricity for electric vehicles in WA. Financial aid (around AUD 4,200 for BEV and AUD 1,100 for PHEV) along with a 50% reduction in the alternative vehicle registration cost, the removal of GST on alternative vehicle sales, and the enforcement of import duty on gasoline vehicles were, however, required to meet the economic criteria for BEV and PHEV due to high cost of the vehicles. Subsidies would be required for the first few years as alternative fuels are expected to become more sustainable with the improvement of the supply chain and mass production of alternative fuel vehicles. Hydrogen fuel is, however, considered unsustainable for public use at this stage in WA due to the high cost of HFCV. To kick start WA's hydrogen economy, the WA government could consider the use of hydrogen-fueled vehicles in its government fleets.

Sustainable alternative fuel production, which is one of the key requirements for WA to alleviate the fuel security problem, combat climate change, and safeguard human health, is possible in WA with the incorporation of the recommended cleaner production strategies, government support, and initiatives. The proposed framework has the capacity and flexibility to accommodate the sustainability assessment needs of other regions of the world.

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Chapter 7

Conclusions

The proposed LCSA framework has successfully addressed the limitations and deficiencies inherent in other methods and frameworks for the sustainability assessment of fuels.

It has been ascertained that most of the previous studies focused only on the environmental life cycle assessment (ELCA) of alternative fuels. Some studies also include the life cycle costing, whereas the research on the social life cycle assessment fuels is very limited. Furthermore, the existing life cycle assessment (LCA) models and case studies were found incapable of addressing the environmental, social and economic assessment of fuels in a holistic manner. The proposed LCSA framework has overcome this problem by considering the interdependencies among the environmental and socioeconomic aspects of alternative fuels. The ELCA, life cycle costing (LCC) and social life cycle assessment (SLCA) tools have been integrated into a single framework that adopts an iterative feedback process to holistically address the interrelationship between the three pillars of sustainability.

Another major concern about the other studies was their inability to effectively reflect the local and region-specific conditions in the life cycle assessment of fuels. It was observed that the sustainability assessment results for one region could not necessarily be used in another region due to the variability in the conditions. This concern has been successfully addressed during the TBL indicator development phase of the proposed framework. It has also provided a comprehensive platform for the identification and selection of potential fuels based on the local availability of the feedstock and other resources required for the production of alternative fuels. Moreover, the framework was tested using the WA local and region-specific data.

As witnessed in the literature, conducting the assessment of a particular fuel is the only or predominant purpose of almost all of the previous studies on the sustainability assessment of fuels. There were no studies that identify, incorporate and assess the potential strategies to improve the sustainability performance of alternative fuel options to meet the sustainability objectives. This deficiency has been comprehensively addressed in the proposed framework as it employs pre-developed threshold values to select a fuel. Any fuel option that failed to meet the pre-defined threshold was assessed again after incorporating an improvement strategy.

Based on the availability of the feedstock and other resources locally, ethanol-gasoline blend (E65), hydrogen, electricity for BEV and PHEV, and PHEV were identified, assessed and selected as the potential alternatives for sustainability assessment. In the ELCA phase, Global warming potential (GWP), Fossil fuel depletion (FFD), Water consumption (WC), and Land use (LU) were used as the indicators. The fuel option E65 met the sustainability assessment criteria with respect to GWP, WC and FFD but failed to meet the LU threshold due to a large amount of land required to grow the ethanol feedstocks. Hydrogen was the worst option as it failed to meet all the environmental targets mainly due to its high amount of electricity requirements for hydrogen production. The BEV failed to meet the GWP criteria because of the high use of electricity during its usage phase. The PHEV showed higher impact than that of BEV in GWP and FFD indicators due to the use of gasoline for 50% of its travel time. As a result, the PHEV failed to meet FFD and GWP criteria.

The outcome of the ELCA necessitated the incorporation of improvement strategies for all of the alternative fuels. Three strategies, namely, use of E10 in place of gasoline, placement of 180Wp solar cells on vehicles, and cleaner electricity for charging, were considered to make the PHEV environmentally sustainable. Similarly, renewable energy for hydrogen production and cleaner electricity for EV charging were considered for the hydrogen and EV, respectively, to meet the sustainability thresholds for the environmental indicators. The E65 failed to meet the land use criterion, and land required to grow wheat feedstock was found to be the main hotspot. On the other hand, E55 made with only cereal straw and mallee-based ethanol met all the environmental criteria.

The fuel options were then assessed for their social impact using four social indicators; local job creation, conservation of fossil fuel (CFF), occupational health and safety (OHAS) and human health. Ethanol and hydrogen met the threshold values for job creation indicator due to having labour intensive upstream activities including feedstock processing and production. The local job creation potential of EV and PHEV were lower compared to the other two fuels and did not meet the sustainability thresholds due to less labour requirement to produce/process the fuel. In regard to the CFF indicator, hydrogen failed to meet the criteria mainly due to the large amount of fossil fuel use during its production stage if conventional grid electricity is used. Similarly, the PHEV failed to meet the criteria for conservation of fossil fuel due to the use of gasoline during half of its travel time. All the fuel options met the human health criteria except for E65 due to the NO_x level in vehicle exhaust emission which was found to be higher than that of gasoline combustion per VKT. The occupational health and safety (OHAS) were measured based on the respondent’s satisfaction and all the fuel options met the OHAS threshold.

The results of the SLCA indicated that there was a need for strategies to improve the performance of fuels. Local battery production was proposed for the PHEV to meet the local job creation indicator as WA was in an excellent position to be the leader of sustainable battery production hub in the world. Besides, engine control strategies and after-treatment devices were suggested to maintain the consistent NOx reduction compared to gasoline during the use of E55. Subsequently, the SCLA indicators were revised and incorporated into the framework. The PHEV and E55 still failed to meet the criteria for local job creation and human health, respectively. The ELCA results were also re-assessed after incorporating the social improvement strategies, and it was confirmed that the criterial for the ELCA was still met.

The final phase of the assessment was Life cycle costing (LCC) that employed the life cycle cost, carbon reduction credit (CRC) and net benefit as the indicators. Except for the CRC indicator for E65, alternative fuel options failed to meet all the economic sustainability thresholds due to the high cost of fuel and/or vehicle compared to gasoline.

The life cycle costs of environmentally and socially sustainable E55, BEV, PHEV, and hydrogen fuels were found to be 0.10, 0.22, 0.18, and 0.79 AUD/VKT, respectively. The framework revealed that three options, namely, ethanol-gasoline blend E55, BEV, and PHEV, would be completely sustainable in WA after incorporating cleaner production strategies and financial assistance into the LCA analysis. For economic sustainability, E55 required a lesser subsidy (2.1 cents/VKT) compared to other fuel options. To cover the subsidy for EV and PHEV in WA, the removal of GST on vehicle purchase, fifty percent subsidy on vehicle registration, inclusion of import duty on gasoline vehicle and direct financial subsidy during vehicle acquisition were proposed. Hydrogen fuel showed better environmental and social performance when hydrogen was produced from renewable energy. The hydrogen fuel option, however, was found to be unsustainable for public use in WA due to the high cost of the hydrogen vehicle.

Improvement strategies were identified, incorporated and assessed to enhance the applicability of the framework as this would assist policymakers in the selection and adoption of alternative fuels in Western Australia. The framework is very flexible as it allows different fuel options and enables scenario analysis to address the region-specific needs and preferences.

Recommendation for future research

The research work would open further avenues of research in the field of sustainability assessment of fuels. For instance, the study could be extended to explore alternative options for diesel vehicles. Also, more accurate assessments could be done by collecting and using the actual data pertaining to the vehicle exhaust emission (e.g., exhaust emissions for ethanol, gasoline and plug in hybrid vehicles) in Western Australia.

Similarly, the SLCA could be further improved by measuring and utilizing the data for the OHAS indicator based on the number of accidents/incidents when alternative fuel supply chains are fully established. Including the end of life treatment of the vehicle would make the results more realistic. The dynamic nature of the car industry, the indicator and their threshold values may change, necessitating further research and periodic update of the relevant parameters of the framework.

Appendix –A

Authorship statements

Authorship agreement and contribution on:

Najmul Hoque, Ilyas Mazhar and Wahidul Biswas. Application of life cycle assessment for sustainability evaluation of transport fuels. Encyclopaedia of Renewable and Sustainable Materials, Materials Science and Materials Engineering, 2020 (4), 359-369.

Contribution statement for the paper:

Authors	Tasks	Contribution
S M Najmul Hoque	Conceptualization and Methodology, analysis, investigation, data curation, software, writing original draft, visualization, review and editing.	80%
Ilyas Mazhar	Conceptualization & Methodology, review& editing and supervision	10%
Wahidul Biswas	Conceptualization & Methodology, review& editing and supervision	10%

Authorship agreement and contribution on:

Najmul Hoque, Wahidul Biswas, Ilyas Mazhar and Ian Howard "LCSA Framework for Assessing Sustainability of Alternative Fuels for Transport Sector" Chemical Engineering Transactions, 2019, 72, 103-108.

Contribution statement for the paper:

Authors	Tasks	Contribution
S M Najmul Hoque	Conceptualization and Methodology, analysis, investigation, data curation, software, writing original draft, visualization, review and editing.	80%
Wahidul Biswas	Conceptualization & Methodology, review & editing and supervision	10%
Ilyas Mazhar	Conceptualization & Methodology and review & editing and supervision	5%
Ian Howard	review & editing and supervision	5%

Authorship agreement and contribution on:

Najmul Hoque, Wahidul Biswas, Ilyas Mazhar and Ian Howard. Environmental life cycle assessment of alternative fuels for Western Australia's transport sector, *Atmosphere* 2019, *10*(7), 398.

Contribution statement for the paper:

Authors	Tasks	Contribution
S M Najmul Hoque	Conceptualization and Methodology, analysis, investigation, data curation, software, writing original draft, visualization, review and editing.	80%
Wahidul Biswas	Conceptualization & Methodology, review & editing and supervision	10%
Ilyas Mazhar	Conceptualization & Methodology and review & editing and supervision	5%
Ian Howard	review & editing and supervision	5%

Authorship agreement and contribution on:

Najmul Hoque, Wahidul Biswas, Ilyas Mazhar and Ian Howard. "Life cycle sustainability assessment of alternative fuels for Western Australia's transport sector, *Sustainability, 2020, 12(14), 5565*.

Contribution statement for the paper:

Authors	Tasks	Contribution
S M Najmul Hoque	Conceptualization and Methodology, analysis, investigation, data curation, software, writing original draft, visualization, review and editing.	80%
Wahidul Biswas	Conceptualization & Methodology, review & editing and supervision	10%
Ilyas Mazhar	Conceptualization & Methodology and review & editing and supervision	5%
Ian Howard	review & editing and supervision	5%

Authorship agreement and contribution on:

Najmul Hoque, Wahidul Biswas, Ilyas Mazhar and Ian Howard. “Sustainability implications of using hydrogen as an Automotive fuel in Western Australia, Journal of Energy and Power Technology, 2020, 2(3), 1-17.

Contribution statement for the paper:

Authors	Tasks	Contribution
S M Najmul Hoque	Conceptualization and Methodology, analysis, investigation, data curation, software, writing original draft, visualization, review and editing.	80%
Wahidul Biswas	Conceptualization & Methodology, review & editing and supervision	10%
Ilyas Mazhar	Conceptualization & Methodology and review & editing and supervision	5%
Ian Howard	review & editing and supervision	5%

Appendix –B

The description of BEV, PHEV and traditional hybrid cars

Based on the two ways of utilization, electric cars are classified as Plug in Hybrid Electric Vehicle (PHEV) and Battery Electric Vehicle (BEV). PHEVs run by the battery until it uses up the charge and then switches over to liquid fuel mode with the aid of a gasoline engine (**Figure A-1**). Batteries of PHEVs can be charged from outside electricity by using a charger when required. Vehicle can run either electric mode or gasoline mode or both modes simultaneously (depends on the design). PHEVs increase the fuel efficiency and reduce the exhaust emissions compared to a dedicated gasoline vehicle. These Vehicles, however, are not fully free from exhaust emission as gasoline is also used as fuel as well as electricity. PHEVs are also complex due to having both gasoline and electric transmission.

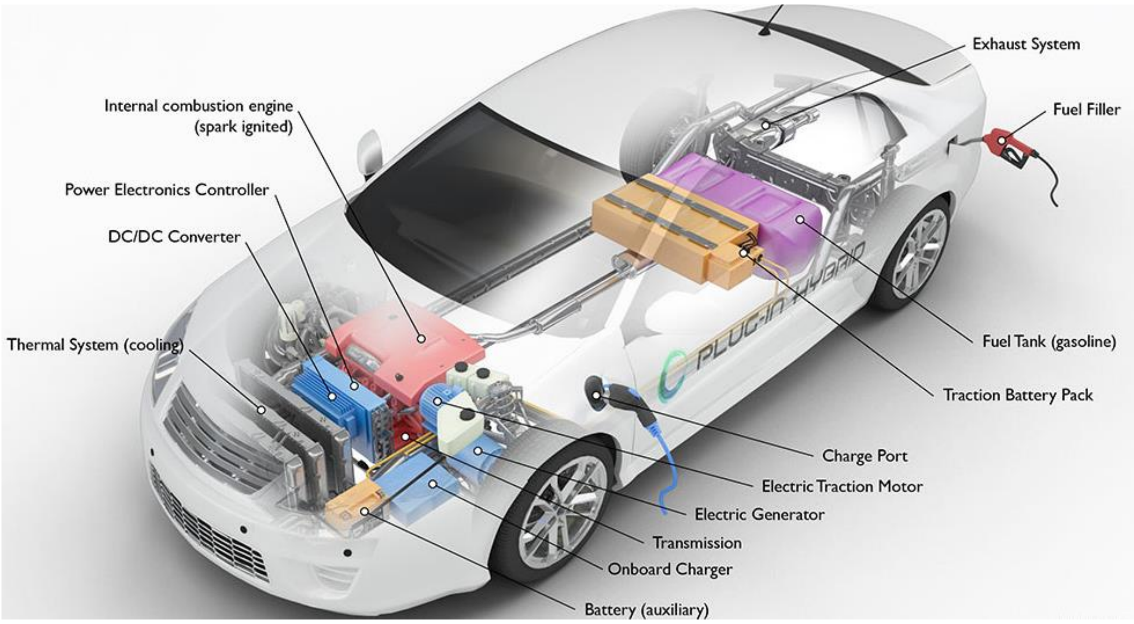

Figure A-1: Plug in hybrid electric vehicle (US Department of Energy, 2018)

Additional main devices of PHEVs other than gasoline vehicles are:

- Charger: It converts the AC charge into DC and charge the battery pack while charging. It also monitors the battery such as state of charge, current and voltage during charging.
- Electric traction motor: Main purpose of the traction motor to run the vehicle wheel by using power from the battery.

- Electric generator: Generates electricity from wheel during braking and by the engine itself. In some vehicles, traction motor acts as both motor and generator so that an extra generator is not required.
- Battery pack: stores electricity during charging and through the traction motor-generator.
- Power electronics controller: it controls the speed of the traction motor by controlling the flow of electricity from battery.
- DC/DC converter: The purpose of this device is to convert high voltage DC from battery to low voltage DC to power the vehicle's auxiliary device.
- Transmission: The PHEV transmission system delivers power to the wheel from engine and electric motor.

On the other hand, there is no gasoline engine, fuel tank and exhaust system in BEVs (**Figure A-2**) and the cars run solely by batteries. BEVs, however, require larger battery bank and electric motor compared to PHEV as electric transmission is the only option to operate the vehicle (US Department of Energy, 2018). There is no tail pipe emission or scope 1 emission during the use of BEVs, and this is one of the main advantages of electricity as a transport fuel. Scope 1 emission is often termed as direct emission to the atmosphere from an activity (i.e. tail pipe emission from vehicle in this case) (Clean Energy Regulator, 2018). Therefore, these vehicles can mitigate the health impact caused by the direct exposures of tail pipe emission from fossil fuel vehicles though the environmental implications caused during the production of electricity (scope 2 emission) need to be assessed.

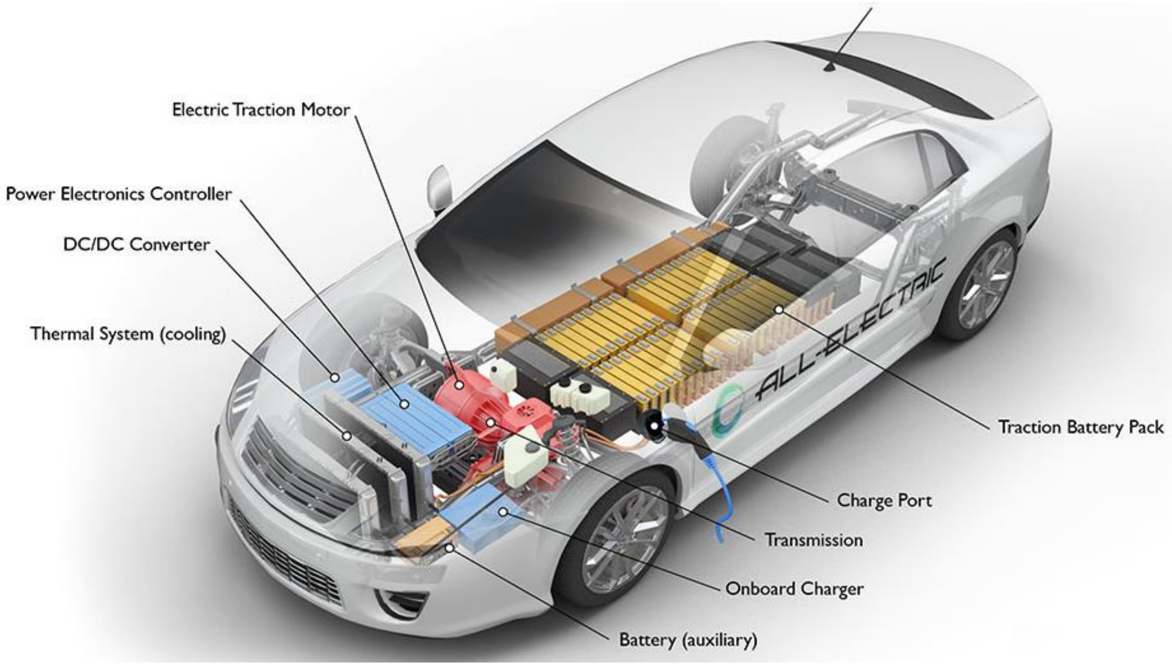

Figure A-2: Battery electric vehicle (US Department of Energy, 2018)

Unlike PHEV and BEV, the traditional/conventional hybrid vehicles cannot be charged from outside electricity. The gasoline is the only fuel for this type of car. The traditional hybrid vehicles use slightly bigger battery than the conventional gasoline which can improve the fuel economy during city driving by capturing the energy while braking and idling. Some traditional hybrid cars, depending on the design, can also be run in low speed by electric mode as well if there is a charge remaining in the battery. The traditional/conventional hybrid cars are excluded for this study as those are often excluded during counting or reporting of electric vehicles as gasoline is the only fuel for this car (Climate Works, 2017; IEA, 2017).

Hydrogen Fuel Cell Vehicle (HFCV)

Direct use of hydrogen in an IC engine is not yet suitable as it causes pre ignition, high pressure rise, unstable combustion, knocking and backfiring (Sharma et al., 2015; Verhelst, 2014). These issues are needed to be taken account in designing of IC engine which will use hydrogen as a gaseous fuel directly as like CNG. Hydrogen, however, as a fuel cell mode is successfully implemented in a Hydrogen Fuel Cell Vehicle (HFCV). HFCV uses hydrogen as a fuel and air as an oxygen sources. When hydrogen is passed through the one side of the membrane, it splits into proton and electron. The membrane itself is the electron barrier but proton goes through it. So, electrons those must go through an external path pass through a traction motor and supplies torque to drive the car. When electrons come back to the other side then mix with the protons and oxygens which results water.

As shown in **Figure A-3**, key components of HFCVs are as follows:

- Hydrogen tank: To store, carry and supply hydrogen to fuel cell.
- Fuel cell stack: To produce electricity by using hydrogen and oxygen.
- Battery Pack: Battery in HFCV stores energy from regenerative braking and provide supplementary power to the traction motor.
- Electric traction motor: Receives power from fuel cell and traction battery pack to drive the car. In most of the cases, this motor also acts as generator to perform both vehicles driving and regenerative functions.
- Transmission (electric): To transfer mechanical power to the wheel from traction motor.
- Battery (auxiliary): To start the car before the traction battery pack is engaged. This battery also powers the vehicle accessories.
- DC/DC Converter: To provide low voltage DC to the vehicle accessories from high voltage traction battery. Auxiliary battery also gets charge from traction battery through this converter.

As like EVs, there are also power electronics controller, and cooling systems according to the requirement of the fuel cell stack and power electronics.

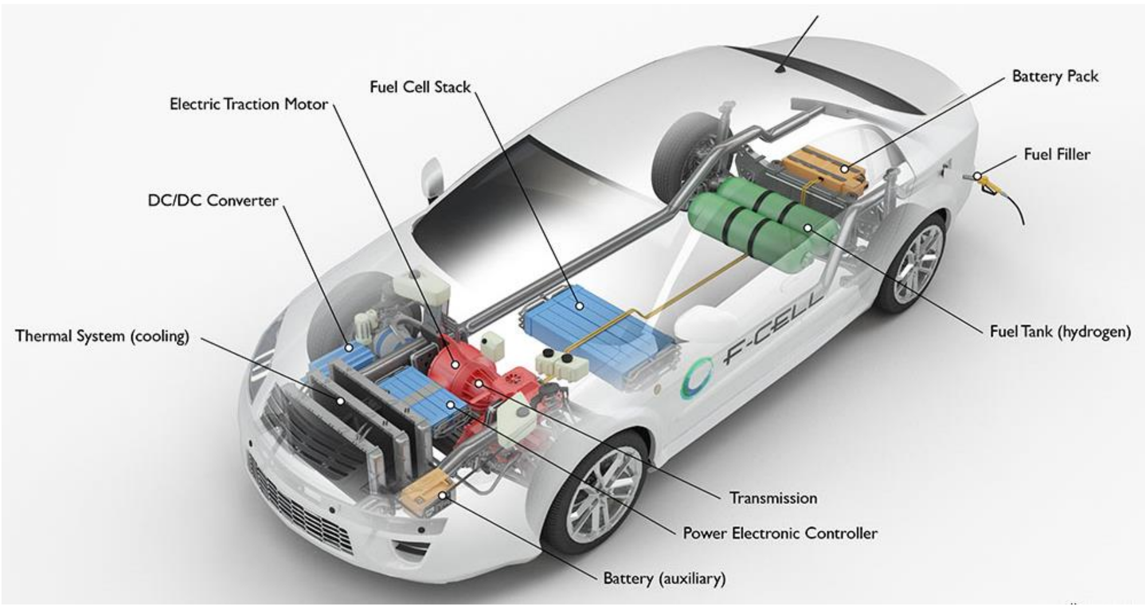

Figure A-3: working of hydrogen fuel cell vehicle (US Department of Energy, 2018)

Appendix-C

Ethics approval and questionnaire for indicator development survey

Curtin University

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07-Mar-2019

Name: Ilyas Mazhar
Department/School: School of Civil and Mechanical Engineering (CME)
Email: I.Mazhar@curtin.edu.au

Dear Ilyas Mazhar

RE: Ethics Office approval
Approval number: HRE2019-0101

Thank you for submitting your application to the Human Research Ethics Office for the project **Developing an integrated framework to assess the sustainability potential of alternative fuels – a life cycle approach**.

Your application was reviewed through the Curtin University Negligible risk review process.

The review outcome is: **Approved**.

Your proposal meets the requirements described in the National Health and Medical Research Council's (NHMRC) *National Statement on Ethical Conduct in Human Research (2007)*.

Approval is granted for a period of one year from **07-Mar-2019** to **06-Mar-2020**. Continuation of approval will be granted on an annual basis following submission of an annual report.

Personnel authorised to work on this project:

Name	Role
Mazhar, Ilyas	CI
Hoque, S M Najmul	Student
Biswas, Wahidul	Co-Inv

Approved documents:

Document

Standard conditions of approval

1. Research must be conducted according to the approved proposal
2. Report in a timely manner anything that might warrant review of ethical approval of the project including:
   - proposed changes to the approved proposal or conduct of the study
   - unanticipated problems that might affect continued ethical acceptability of the project
   - major deviations from the approved proposal and/or regulatory guidelines
   - serious adverse events
3. Amendments to the proposal must be approved by the Human Research Ethics Office before they are implemented (except where an amendment is undertaken to eliminate an immediate risk to participants)

4. An annual progress report must be submitted to the Human Research Ethics Office on or before the anniversary of approval and a completion report submitted on completion of the project
5. Personnel working on this project must be adequately qualified by education, training and experience for their role, or supervised
6. Personnel must disclose any actual or potential conflicts of interest, including any financial or other interest or affiliation, that bears on this project
7. Changes to personnel working on this project must be reported to the Human Research Ethics Office
8. Data and primary materials must be retained and stored in accordance with the Western Australian University Sector Disposal Authority (WAUSDA) and the Curtin University Research Data and Primary Materials policy
9. Where practicable, results of the research should be made available to the research participants in a timely and clear manner
10. Unless prohibited by contractual obligations, results of the research should be disseminated in a manner that will allow public scrutiny; the Human Research Ethics Office must be informed of any constraints on publication
11. Approval is dependent upon ongoing compliance of the research with the Australian Code for the Responsible Conduct of Research, the National Statement on Ethical Conduct in Human Research, applicable legal requirements, and with Curtin University policies, procedures and governance requirements
12. The Human Research Ethics Office may conduct audits on a portion of approved projects.

Special Conditions of Approval

This letter constitutes low risk/negligible risk approval only. This project may not proceed until you have met all of the Curtin University research governance requirements.

Should you have any queries regarding consideration of your project, please contact the Ethics Support Officer for your faculty or the Ethics Office at hrec@curtin.edu.au or on 9266 2784.

Yours sincerely

Amy Bowater
Ethics, Team Lead

Participant Information Statement

Dear Respondent,

I would like to thank you for your kind participation in this survey that will assist me in the selection of triple bottom line indicators for my PhD research project titled, "Developing an integrated framework to assess the sustainability potential of alternative fuels – a life cycle approach". I intend to use life cycle assessment to identify and quantify the indicators for social, economic and environmental performance assessment of alternative transport fuels in Western Australia.

An intensive literature review has already been completed to gather information about the indicators that are generally used for sustainability assessment of alternative transport fuels. As these indicators vary depending on the factors, such as socio-economic status and resource availability, your expert opinion will be highly beneficial as well as crucial to make this study realistic and reliable. This survey aims at gathering responses from experts in the areas, such as academia, government and industry to estimate the level of relevance of the proposed indicators.

The participation in this survey is completely voluntary and you can withdraw at any stage of the survey if you want. Your details will not be disclosed in any publications or thesis. If you decide to withdraw at any point, all the information provided by you will be deleted. It will take around 5 minutes to read the instructions and another 10-15 minutes to complete the survey.

'The information collected in this research will be re-identifiable (coded) which means identifying information will be removed and replaced with a code. Only the research team have access to the code and any information we collect will be treated as confidential and used only in this project. The research team and the Curtin University Ethics Committee will have access to the information we collect. Electronic data will be password-protected and kept under secure conditions at Curtin University for 7 years after the research has ended and then it will be destroyed. You have the right to access, and request correction of, your information in accordance with relevant privacy laws.' "Curtin University Human Research Ethics Committee (HREC) has approved this study (HRE 2019-0101). Should you wish to discuss the study with someone not directly involved, in particular, any matters concerning the conduct of the study or your rights as a participant, or you wish to make a confidential complaint, you may contact the Ethics Officer on (08) 9266 9223 or the Manager, Research Integrity on (08) 9266 7093 or email hrec@curtin.edu.au."

Should you have any question or further clarification regarding the survey please feel free to contact me, S M Najmul Hoque on smnajmul.hoque@postgrad.curtin.edu.au or my supervisors Dr. Ilyas Mazhar on i.mazhar@curtin.edu.au and Associate Professor Wahidul Biswas on w.biswas@curtin.edu.au . We are happy to discuss any concerns (if any) during this survey.

Curtin University

Consent

Question: Have you read the participant information statement, and do you consent to participate in this questionnaire?

Respondent's answer: Yes/No

Question: Please provide your email address.

Respondent's answer:

A. Relevance of Environmental Indicators

Global Warming Potential (GWP)

It is the total greenhouse gas that is expected over the life cycle (agriculture, production, transportation and use) of an alternative fuel. GWP can cause rises in sea level, extreme weather events and may bring new diseases. These phenomena can ultimately affect the eco-system function, human health and biodiversity. GWP will be measured in kgCO_2-eq per vehicle kilometre travelled (VKT).

Question: Is "Global Warming Potential" a relevant indicator in the sustainability assessment of alternative transport fuel?

Respondent's answer: Yes / No

If No, please briefly explain the reasons.

Eutrophication

Eutrophication occurs due to the release of nitrogen, phosphorous and organic compound from the life cycle of alternative fuels. Eutrophication can damage ecosystem quality by increasing plant diseases and decreasing the pest susceptibility. It can also lead to change in species composition due to the algal growth, reduction of oxygen and sunlight infiltration in water. It will be measured in kg of PO_4 eq /VKT.

Question: Is "Eutrophication" a relevant indicator in the sustainability assessment of alternative transport fuel?

Respondent's answer: Yes / No

If No, please briefly explain the reasons.

Resources depletion- fossil fuel

It is the amount of non-renewable energy (extracted from natural sources such as coal, oil and natural gas) consumed by the alternative fuel during its entire life cycle (agricultural, conversion and transportation stages of alternative fuel). It will be measured as MJ/VKT.

Question: Is “Resource depletion-fossil fuel” a relevant indicator in the sustainability assessment of alternative transport fuel?

Respondent’s answer: Yes / No

If No, please briefly explain the reasons.

<u>Water use</u>

Amount of water that is taken from the environment (from underground; ground surface such as rivers and lakes; manmade or natural storages) during the life cycle (such as agricultural cultivation of feedstock: irrigation, different chemicals and fertilizer production; water required for alternative fuel production) of an alternative fuel, causing water scarcity and damaging the natural environment. It will be measured based on Cubic metres of water/VKT.

Question: Is “Water Use” a relevant indicator in the sustainability assessment of alternative transport fuel?

Respondent’s answer: Yes / No

If No, please briefly explain the reasons.

<u>Land use</u>

Land use area that is required due to the agricultural cultivation of feedstock, processing and different chemical production requirements during the life cycle of alternative fuels. This land use change affects both natural and man-made environments. It will be measured as ha.a/VKT.

Question: Is “Land Use” a relevant indicator in the sustainability assessment of alternative transport fuel?

Respondent’s answer: Yes / No

If No, please briefly explain the reasons.

More Indicators (optional)

Question: Would you like to suggest any other environmental indicator(s) of alternative transport fuel?

Respondent's answer: Yes/No

If No, please scroll to the bottom of the page and press next to launch social indicator selection

If Yes, please provide your suggestions in the following questions.

- New indicator 1:
  Why do you think that it is important for this study?
- New indicator 2:
  Why do you think that it is important for this study?
- New indicator 3:
  Why do you think that it is important for this study?
- New indicator 4:
  Why do you think that it is important for this study?

B: Relevance of Social Indicators

Local job creation

Alternative fuel has the potential to create jobs (e.g. job creation during the production of alternative fuel) locally. Direct job creation will be measured under the study as job creation/VKT.

Question: Is "Local job creation" a relevant indicator in the sustainability assessment of alternative transport fuel?

Respondent's answer: Yes / No

If No, please briefly explain the reasons.

Conservation of fossil fuel

It will be measured, in Litres/VKT, based on the substitution of fossil fuel due to the use of alternative fuels in WA.

Question: Is "Conservation of fossil fuel" a relevant indicator in the sustainability assessment of alternative transport fuel?

Respondent's answer: Yes / No

If No, please briefly explain the reasons.

Occupational health and safety

This will measure the potential health and safety issues over the life cycle of alternative fuel. It will be measured based on respondent level of satisfaction.

Question: Is "Occupational health and safety" a relevant indicator in the sustainability assessment of alternative transport fuel?

Respondent's answer: Yes / No

If No, please briefly explain the reasons.

Human/public health

This indicator will consider the difference in vehicle exhaust emission (use phase of fuel) between alternative fuel options and traditional fuel. Direct exposure of vehicle exhaust emission at low elevation (such as CO, NO_x and PM) can cause severe human health damage. It will be measured in kg/VKT.

Question: Is "Human/public health" a relevant indicator in the sustainability assessment of alternative transport fuel?

Respondent's answer: Yes / No

If No, please briefly explain the reasons.

Social acceptability

This indicator will measure the favourability of alternative fuel options compared to traditional fuel as the reason of acceptance. Disapproval will help to formulate proper policy for a particular reason. It will be measured based on the respondent's level of satisfaction.

Question: Is "Social acceptability" a relevant indicator in the sustainability assessment of alternative transport fuel?

Respondent's answer: Yes / No

If No, please briefly explain the reasons.

More Indicators (optional)

Question: Would you like to suggest any other social indicator(s) of alternative transport fuel?

Respondent's answer: Yes/No

If No, please scroll to the bottom of the page and press next to launch economic Indicator selection

If Yes, please provide your suggestions in the following questions.

- New indicator 1:
  Why do you think that it is important for this study?
- New indicator 2:
  Why do you think that it is important for this study?
- New indicator 3:
  Why do you think that it is important for this study?
- New indicator 4:

Why do you think that it is important for this study?

C. Relevance of Economic indicators

Life cycle cost

The Life cycle cost is the estimation of total cost of materials, feedstock and energy required to produce alternative fuels plus additional cost due to any vehicle changes required for using alternative fuels. It will be measured in AUD/VKT.

Question: Is "Life cycle cost" a relevant indicator in the sustainability assessment of alternative transport fuel?

Respondent's answer: Yes / No

If No, please briefly explain the reasons.

Net benefit

This indicator is the net benefit for each user per VKT resulting from the cost difference between traditional and alternative fuel options which will be measured in AUD/VKT.

Question: Is "Net benefit" a relevant indicator in the sustainability assessment of alternative transport fuel?

Respondent's answer: Yes / No

If No, please briefly explain the reasons.

Carbon reduction credit

This is the potential additional benefit due to the reduction in carbon footprint over the life cycle of alternative fuels compared to traditional fuels which will be measured in AUD/VKT. Whilst carbon tax is not currently applied in Australia, it is incorporated to see the implication of a carbon tax on the performance of alternative fuels.

Question: Is “Carbon reduction credit” a relevant indicator in the sustainability assessment of alternative transport fuel?

Respondent’s answer: Yes / No

If No, please briefly explain the reasons.

More Indicators (optional)

Question: Would you like to suggest any other economic indicator(s) of alternative transport fuel?

Respondent’s answer: Yes/No

If No, please scroll to the bottom of the page and press submit

If Yes, please provide your suggestions in the following questions.

- New indicator 1:
  Why do you think that it is important for this study?
- New indicator 2:
  Why do you think that it is important for this study?
- New indicator 3:
  Why do you think that it is important for this study?
- New indicator 4:
  Why do you think that it is important for this study?

Ethics approval and questionnaire for occupational health and safety survey

Curtin University

Research Office at Curtin

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Perth Western Australia 6845

Telephone +61 8 9266 7863
Facsimile +61 8 9266 3793
Web research.curtin.edu.au

25-Sep-2019

Name: Ilyas Mazhar
Department/School: School of Civil and Mechanical Engineering (CME)
Email: I.Mazhar@curtin.edu.au

Dear Ilyas Mazhar

RE: Ethics Office approval
Approval number: HRE2019-0642

Thank you for submitting your application to the Human Research Ethics Office for the project **Developing an integrated framework to assess the sustainability potential of alternative fuels – a life cycle approach.**

Your application was reviewed through the Curtin University Negligible risk review process.

The review outcome is: **Approved.**

Your proposal meets the requirements described in the National Health and Medical Research Council's (NHMRC) *National Statement on Ethical Conduct in Human Research (2007).*

Approval is granted for a period of one year from **25-Sep-2019** to **24-Sep-2020**. Continuation of approval will be granted on an annual basis following submission of an annual report.

Personnel authorised to work on this project:

Name	Role
Mazhar, Ilyas	CI
Biswas, Wahidul	Co-Inv
Hoque, S M Najmul	Student

Approved documents:

Document

Standard conditions of approval

1. Research must be conducted according to the approved proposal
2. Report in a timely manner anything that might warrant review of ethical approval of the project including:
    - proposed changes to the approved proposal or conduct of the study
    - unanticipated problems that might affect continued ethical acceptability of the project
    - major deviations from the approved proposal and/or regulatory guidelines
    - serious adverse events
3. Amendments to the proposal must be approved by the Human Research Ethics Office before they are implemented (except where an amendment is undertaken to eliminate an immediate risk to participants)

4. An annual progress report must be submitted to the Human Research Ethics Office on or before the anniversary of approval and a completion report submitted on completion of the project
5. Personnel working on this project must be adequately qualified by education, training and experience for their role, or supervised
6. Personnel must disclose any actual or potential conflicts of interest, including any financial or other interest or affiliation, that bears on this project
7. Changes to personnel working on this project must be reported to the Human Research Ethics Office
8. Data and primary materials must be retained and stored in accordance with the Western Australian University Sector Disposal Authority (WAUSDA) and the Curtin University Research Data and Primary Materials policy
9. Where practicable, results of the research should be made available to the research participants in a timely and clear manner
10. Unless prohibited by contractual obligations, results of the research should be disseminated in a manner that will allow public scrutiny; the Human Research Ethics Office must be informed of any constraints on publication
11. Approval is dependent upon ongoing compliance of the research with the Australian Code for the Responsible Conduct of Research, the National Statement on Ethical Conduct in Human Research, applicable legal requirements, and with Curtin University policies, procedures and governance requirements
12. The Human Research Ethics Office may conduct audits on a portion of approved projects.

Special Conditions of Approval
Nil

https://www.nhmrc.gov.au/guidelines-publications/r39

This letter constitutes low risk/negligible risk approval only. This project may not proceed until you have met all of the Curtin University research governance requirements.

Should you have any queries regarding consideration of your project, please contact the Ethics Support Officer for your faculty or the Ethics Office at hrec@curtin.edu.au or on 9266 2784.

Yours sincerely

Amy Bowater
Ethics, Team Lead

Participant Information Statement

Dear Respondent,

I would like to thank you for your kind participation in this survey that will assist me to measure the satisfaction level of safety features of potential future alternative fuel options for WA transport sector under my PhD research project titled, “Developing an integrated framework to assess the sustainability potential of alternative fuels – a life cycle approach”. Alternative fuel such as (i) Ethanol E65 (i.e. 35% gasoline and 65% ethanol) from three local feedstocks (such as wheat, grain straw and mallee wood); (ii) Hydrogen (produced through water electrolysis) for hydrogen fuel cell vehicle (HFCV); (iii) Electricity for Electric Vehicle (EV); and (iv) Electricity and gasoline for Plug in Hybrid Vehicle (PHEV) are selected for assessment as alternatives of gasoline. This survey aims at gathering responses from the local supply chain participants (people who are knowledgeable about alternative fuel production, supply and use) to determine the satisfaction level regarding the potential safety features of these future fuels and corresponding vehicles. The 5-point Likert scale is used for the response where 1 is the least satisfaction, 5 is the required level of satisfaction (threshold value). If you answer is less than 5 then also, please write the reason of potential risk and how to overcome the risk.

The participation in this survey is completely voluntary and you can withdraw at any stage of the survey. Your details will not be disclosed in any publications or thesis. If you decide to withdraw at any point, all the information provided by you will be deleted. There is no mandatory question in the survey (participant can proceed without giving answer of any particular question if they want). The survey will take around 5 minutes to read the instructions and another 5 minutes to complete the survey.

'The information collected in this research will be re-identifiable (coded) which means identifying information will be removed and replaced with a code. Only the research team have access to the code and any information we collect will be treated as confidential and used only in this project. The research team and the Curtin University Ethics Committee will have access to the information we collect. Electronic data will be password-protected and kept under secure conditions at Curtin University for 7 years after the research has ended and then it will be destroyed. You have the right to access, and request correction of, your information in accordance with relevant privacy laws.' "Curtin University Human Research Ethics Committee (HREC) has approved this study (HRE 2019-0642). Should you wish to discuss the study with someone not directly involved, in particular, any matters concerning the conduct of the study or your rights as a participant, or you wish to make a confidential complaint, you may contact the Ethics Officer on (08) 9266 9223 or the Manager, Research Integrity on (08) 9266 7093 or email hrec@curtin.edu.au." If you have any question or further clarification regarding the survey please feel free to contact me, S M Najmul Hoque on smnajmul.hoque@postgrad.curtin.edu.au or my supervisors Dr. Ilyas Mazhar on i.mazhar@curtin.edu.au or Dr. Wahidul Biswas on w.biswas@curtin.edu.au We are happy to discuss any concerns (if any) during this survey.

Curtin University

Consent

Question: Have you read the participant information statement, and do you consent to participate in this questionnaire?

Respondent's answer: Yes/No

Question: Please provide your email address.

Respondent's answer:

Section 1: Ethanol

This section will measure the satisfaction level of participants regarding the potential safety features about ethanol fuel supply chain in different stages of its life cycle such as (i) Agriculture of feedstocks (wheat, grain straw, mallee wood) (ii) Conversion to ethanol; (iii) Transportation of ethanol from production plant to blending station and distribution as E65 (65% ethanol and 35% gasoline); (iv) Use of E65 in ethanol flexi fuel vehicle.

Question 1a.

Are you satisfied with the safety features during the agriculture of ethanol feedstocks; production of ethanol; transportation and distribution; and use of ethanol as E65 in the ethanol vehicle (1 is the lowest satisfaction, and 5 is the required level of satisfaction)?

Response:

Different stages	Level of satisfaction	
	Based on the possibility of occurrence of injuries	Based on the possibility of having hazardous or disturbing environment (e.g., noise)
Agriculture of feedstocks (wheat grain, grain straw and Mallee wood)	1/2/3/4/5/Neutral	1/2/3/4/5/Neutral
Conversion to ethanol	1/2/3/4/5/Neutral	1/2/3/4/5/Neutral
Transportation and distribution of ethanol	1/2/3/4/5/Neutral	1/2/3/4/5/Neutral
Use of ethanol as E65 in Ethanol flexi fuel vehicle (passenger car)	1/2/3/4/5/Neutral	1/2/3/4/5/Neutral

Question 1b.

If any of your answer in the previous question is less than 5, please write the reason of potential hazard from these future-based potential fuel supply chains and how to overcome the probable hazards (or what needs to be done to make you score 5 or more).

Response:

…………………………………………………………………………………………………

……………………………………………………………………………………………..

Section 2: Hydrogen

This section will measure the satisfaction level of participants regarding the potential safety features about hydrogen fuel supply chain in different stages of its life cycle such as (i) Fuel production (water electrolysis); (ii) Fuel distribution to the retailers by tube tankers; (iii) use of hydrogen in hydrogen fuel cell vehicle and iv) Production of hydrogen fuel cell vehicle components (components and final assembly).

Question 2a.

Are you satisfied with the safety features during hydrogen production, distribution, use of hydrogen in vehicle and production phase of hydrogen fuel cell vehicle (1 is the lowest satisfaction, and 5 is the required level of satisfaction)?

Response:

Different stages	Level of satisfaction	
	Based on the possibility of occurrence of injuries	Based on the possibility of having hazardous or disturbing environment (e.g., noise)
Hydrogen production	1/2/3/4/5/Neutral	1/2/3/4/5/Neutral
Distribution of hydrogen to the retailers	1/2/3/4/5/Neutral	1/2/3/4/5/Neutral
Use phase in vehicle (passenger car)	1/2/3/4/5/Neutral	1/2/3/4/5/Neutral
Vehicle production phase	1/2/3/4/5/Neutral	1/2/3/4/5/Neutral

Question 2b.

If any of your answer in the previous questions is less than 5, please write the reason of potential safety hazard and how to overcome the hazard (or what needs to be done to make you score 5 or more).

Response:

…………………………………………………………………………………………………

…………………………………………………………………………………………………

…………………………………………………………………………………………………

Section 3: Electric vehicle (EV)

This section will measure the satisfaction level of participants regarding the potential safety features of electricity as fuel in during different stages of its life cycle such as (i) Electricity production; (ii) Electricity distribution and transportation to the users; (iii) use of electricity in electric vehicle and iv) production of electric vehicle components (components and final assembly).

Question 3a.

Are you satisfied with the safety features during the production of electricity, electricity transmission and distribution to the users, use of electricity in electric vehicle and production of electric vehicle (1 is the lowest satisfaction, and 5 is the required level of satisfaction)?

Response:

Different stages	Level of satisfaction	
	Based on the possibility of occurrence of injuries	Based on the possibility of having hazardous or disturbing environment (e.g., noise)
Electricity Production	1/2/3/4/5/Neutral	1/2/3/4/5/Neutral
Transmission and distribution of electricity	1/2/3/4/5/Neutral	1/2/3/4/5/Neutral
Use of electricity in electric vehicle (passenger car)	1/2/3/4/5/Neutral	1/2/3/4/5/Neutral
Vehicle production phase	1/2/3/4/5/Neutral	1/2/3/4/5/Neutral

Question 3b.

If your answer in the previous question is less than 5, please write the reason of potential safety hazard and how to overcome the safety hazard (or what needs to be done to make you score 5 or more).

Response:

…………………………………………………………………………………………………

……………………………………………………………………………………………….....

Section 4: Plug in hybrid electric vehicle (PHEV)

This section will measure the satisfaction level of participants regarding the potential safety features of plug in electric vehicle during its driving (its use phase only). PHEV is considered because it uses both electricity and gasoline as fuel.

Question 4a.

Are you satisfied with the safety features during the use of plug in electric vehicle (1 is the lowest satisfaction, and 5 is the required level of satisfaction)?

Response:

	Level of satisfaction	
	Based on the possibility of occurrence of injuries	Based on the possibility of having hazardous or disturbing environment (e.g., noise)
Use of plug in electric vehicle (passenger car)	1/2/3/4/5/Neutral	1/2/3/4/5/Neutral

Question 4b.

If your answer in the previous question is less than 5, please write the reason of potential safety hazard and how to overcome the safety hazard (or what needs to be done to make you score 5 or more).

Response:

……………………………………………………………………………………………………

…………………………………………………………………………………………………....

Respondent response for TBL Indicator selection

Used symbols in the table:

A= Respondent from academic category (Academia who are associated with alternative fuel and vehicle research), G= Respondent from government category (Government employee are associated with alternative fuel policy and research) , I= Respondent from Industry category (alternative fuel and vehicle industry), **Indicators:** E1: GWP, E2= Eutrophication, E3= FFD, E4=WC, E5=Land use, S1= Local job creation, S2= conservation of fossil fuel (CFF), S3=OHAS S4=Human health, S5=Social acceptability, Ec1=LCC, Ec2=net benefit and Ec=Carbon reduction Credit. Yes= Respondent thinks that this indicator is important for this study, N= Respondent thinks that this indicator is not important for this study.

Sr.	Category	Environmental Indicator					Social Indicators					Economic		
		E-1	E-2	E-3	E-4	E-5	S-1	S-2	S-3	S-4	S-5	Ec-1	Ec-2	Ec-3
1	A	Yes	Yes	Yes	N	N	N	N	N	N	N	Yes	N	N
2	G	-	-	-	-	-	Yes	Yes	N	Yes	N	N	N	Yes
3	I	N	N	Yes	N	N	N	Yes	Yes	N	N	Yes	Yes	N
4	I	Yes								Yes				
5	I	Yes	-	Yes	-	-	Yes	-	-	Yes	Yes	Yes	-	Yes

6	I	N	N	N	Yes	Yes	Yes	N	Yes	Yes	Yes	Yes	Yes	N
7	I	Yes	Yes							Yes			Yes	
8	I	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
9	I	Yes	N	Yes	Yes	N	N	Yes	N	Yes	N	Yes	Yes	Yes
10	G	Yes	Yes	N	Yes	Yes	Yes	N	Yes	Yes	Yes	Yes	Yes	Yes
11	I	Yes	-	Yes	Yes	N	-	-	Yes	Yes	-	Yes	-	Yes
12	G	-	-	-	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
13	G	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
14	G	Yes	Yes	Yes	Yes	Yes	Yes	N	N	Yes	Yes	Yes	Yes	Yes
15	A	N	Yes	N	Yes	Yes	Yes	Yes	N	N	Yes	Yes	Yes	N
16	G	Yes	Yes	N	Yes	Yes	Yes	N	N	Yes	N	Yes	N	Yes
17	G	Yes	Yes	N	Yes	Yes	N	N	Yes	Yes	N	Yes	Yes	N
18	A	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

19	A	Yes	N	Yes	Yes	Yes	Yes	Yes	N	N	Yes	Yes	Yes	N
20	A	Yes	N	Yes	Yes	N	Yes	Yes	N	Yes	N	Yes	N	N
21	A	Yes	N	Yes	Yes	Yes	N	Yes	N	Yes	N	Yes	Yes	Yes
22	G	Yes	Yes	N	Yes	Yes	Yes	N	Yes	Yes	Yes	Yes	Yes	N
23	A	Yes	N	Yes	N	N	Yes	Yes	N	Yes	N	Yes	Yes	Yes
24	A	Yes	N	Yes	Yes	Yes	Yes	N	Yes	Yes	N	Yes	Yes	Yes
25	A	Yes	N	Yes	N	N	N	N	Yes	Yes	N	Yes	Yes	Yes
26	G	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	N	Yes	Yes	N
27	I	Yes	Yes	Yes	Yes	Yes	N	N	N	Yes	N	N	N	N
28	A	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	N	Yes	Yes	N
29	I	Yes	N	Yes	Yes	Yes	Yes	Yes	N	Yes	Yes	Yes	N	Yes
30	G	Yes	N	Yes	N	N	Yes	N	N	Yes	N	Yes	N	N

Appendix-D

Data summary for social and economic indicators

Table A-1: Job creation through different activities in mallee plantation and grain farming (by farmers and contractors)

Activities	unit	Job creation (Job-hrs)	remarks
1. Mallee plantation establishment and harvest			
Initial planning of advisor	1 gmt*	2.22E-04	Based on Wu et al., 2007
Site inspection by advisor	1 gmt	2.22E-04	Same as above
Site supervision by advisor	1 gmt	2.22E-04	Same as above
Contract marking out and mapping	1 gmt	6.67E-04	Same as above
earthworks by farmer	1 gmt	1.11E-03	Same as above
weed control	1 gmt	1.11E-04	Same as above
monitoring of mallee seedling production at nursery	1 gmt	2.22E-04	Same as above
transport of seedlings from nursery to site	1 gmt	2.78E-04	Same as above
Planting	1 gmt	1.56E-02	Same as above
monitoring of newly planted seedling	1 gmt	6.67E-04	Same as above
spring weed control	1 gmt	1.11E-04	Same as above
Pesticide	1 gmt	1.11E-04	Same as above
2nd year weed control	1 gmt	1.11E-04	Same as above
Mallee harvest	1 gmt	1.67E-02	Based on Weldegiorgis et al., 2014
2. grain farming			
Planting	1 L ethanol	1.58E-04	Based on 0.12 hours/ha (Biswas et al., 2008)
Spraying	1 L ethanol	3.95E-04	Based on 0.03 hours/ha (Biswas et al., 2008)
Harvesting	1 L ethanol	1.05E-04	Based on 0.08 hours/ha (Biswas et al., 2008)
Top dressing	1 L ethanol	1.58E-04	Based on 0.12 hour/ha (Biswas et al., 2008)
3. Others			
Straw harvest	1 L ethnaol	4.97E-05	Based on Stucley et al., 2012
Straw baling and handling	1 l ethanol	1.84E-04	Based on Stucley et al., 2012

*green metric tonne of mallee

Table A-2: Data summary for LCC (All costs are in AUD 2018)

input	category	unit	Cost (AUD)	Remarks
1. Cost of different inputs				
Flexi N	fertilizer	kg	4.50E-01	Based on local suppliers
Urea	fertilizer	kg	5.30E-01	Same as above
DAP	fertilizer	kg	5.60E-01	Same as above
Lime	chemical	tonne	1.00E+01	Based on department of Agriculture, WA
Glyphosate	Herbicide	L	8.00E+00	Weed control in winter crops 2018 (Brook and Mcmaster, 2018)
Crusader	Herbicide	L	7.92E+01	Lupin Agronomy, WA (Elders Australia, 2016)
Gramoxone	Herbicide	L	9.49E+00	Weed control in winter crops 2018 (Brook and Mcmaster, 2018)
Logran	Herbicide	kg	2.17E+02	Same as above
MCPA 242	Herbicide	L	1.09E+01	Same as above

Treflan	Herbicide	L	10.00E+00	Lupin Agronomy, WA (Elders Australia, 2016)
Chlorpyrifos	pesticide	L	1.50E+01	Based on local suppliers
Simazine	herbicide	kg	7.94E+00	Weed control in winter crops 2018 (Brook and Mcmaster, 2018)
Lontrel	herbicide	L	4.21E+01	Same as above
Eclipse	herbicide	L	2.02E+02	Same as above
Verdict	herbicide	L	4.91E+01	Same as above
Sulfuric Acid	chemical	kg	6.90E-01	Based on local suppliers
NaOH	chemical	kg	6.50E-01	AECOM Australia, 2016
Canola oil	-	kg	1.84E+00	Based on local suppliers
Corn steep liquor	chemical	kg	3.00E-01	Same as above
Diesel	fuel	L	1.48E+00	Fuel Watch WA
Ethanol delivery	transportation	tkm	6.90E-02	AECOM Australia, 2016
2. Activities during grain framing				
Seeding	Contractor job	1 tonne grain	2.10E+01	Department of Primary Industries and Regional Development, WA
Spraying	Contractor job	1 tonne grain	8.83E+00	Same as above
Harvesting	Contractor job	1 tonne grain	1.75E+01	Same as above
Top dressing	Contractor job	1 tonne grain	2.10E+01	Same as above
Salaries	Contractor job	1 tonne grain	3.40E+00	Same as above
Plant and equipment	Contractor job	1 tonne grain	2.80E+00	Same as above
3. Mallee Plantation Establishment				
Initial planning of advisor	Contractor job	gmt**	1.59E-02	Based on Wu et al., 2007
Site inspection by advisor	Contractor job	gmt	1.59E-02	Same as above
Site supervision by advisor	Contractor job	gmt	1.59E-02	Same as above
Contract marking out and mapping	Contractor job	gmt	4.77E-02	Same as above
Earthworks by farmer	Contractor job	gmt	3.31E-02	Same as above
Weed control	Contractor job	gmt	3.31E-03	Same as above
Monitoring of mallee seedling production at nursery	Contractor job	gmt	1.59E-02	Same as above
Transport of seedlings from nursery to site	Contractor job	gmt	8.28E-03	Same as above
Planting	Contractor job	gmt	4.64E-01	Same as above
Monitoring of newly planted seedling	Contractor job	gmt	4.77E-02	Same as above
Spring weed control	Contractor job	gmt	3.31E-03	Same as above
Pesticide	Contractor job	gmt	3.31E-03	Same as above
2nd year weed control	Contractor job	gmt	3.31E-03	Same as above
4. Mallee harvest				
Harvest by farmer	Contractor job	gmt	5.11E+00	Based on Stucley et al., 2012
Fertilizer after every harvest	Contractor job	gmt	2.80E-01	Based on Wu et al., 2007
Supply chain management	wage	gmt	4.35E+00	Same as above
5. Others				
Land opportunity cost for mallee plantation	-	gmt	2.18E+01	Based on Stucley et al., 2012

Appendix-E

<u>Sample calculations and data for the improvement strategies</u>

1. Environmental strategy for hydrogen fuel

- Strategy: Renewable electricity (50% wind and 50% solar) for hydrogen production

Item	Base case				After implementing strategies				Reduction from base case
	GWP ($kgCO_2$)	WC (m^3)	LU (ha.a)	FFD (MJ)	GWP ($kgCO_2$)	WC (m^3)	LU (ha.a)	FFD (MJ)	
Electricity per kWh	8.75E-01	1.31E-03	4.39E-06	7.90E+00	1.04E-03	4.95E-06	1.07E-08	1.08E-02	$D_{\text{base case}}$- $D_{\text{after implementing strategy}}$
Hydrogen production plant impact per VKT (A)	4.79E-01	7.19E-04	2.41E-06	4.34E+00	5.87E-04	3.16E-06	6.01E-09	6.17E-03	GWP=4.79E-01
Fuel life cycle (B)	4.95E-01	8.90E-4	2.46E-06	4.57E+00	1.61E-02	1.75E-04	5.45E-08	2.38E-01	WC=7.12E-04
Vehicle materials (C)	6.14E-02	6.03E-4	3.76E-07	7.75E-01	6.14E-02	6.03E-04	3.76E-07	7.75E-01	LU=2.40E-06
Total life cycle impact (D=B+C)	5.57E-01	1.49E-03	2.83E-06	5.34E+00	7.75E-02	7.78E-04	1.64E-07	1.01E+00	FFD=4.32E+00
Life cycle impact of gasoline (E)	2.53E-01	6.19E-04	1.90E-07	2.92E+00	2.53E-01	6.19E-04	1.90E-07	2.92E+00	
Reduction compared to gasoline [(E-D)/E]	-120%	-	-	-83%	69%	-	-	65%	

2. Environmental strategy for EV

- Strategy: Cleaner grid electricity (2030 grid of WA) for EV charging

Item	Base case				After implementing strategy				Reduction from base case
	GWP ($kgCO_2$)	WC (m^3)	LU (ha.a)	FFD (MJ)	GWP ($kgCO_2$)	WC (m^3)	LU (ha.a)	FFD (MJ)	$C_{\text{base case}}$- $C_{\text{after implementing strategy}}$
Electricity per kWh	8.75E-01	1.31E-03	4.39E-06	7.90E+00	5.18E-01	1.25E-03	4.38E-06	5.88E+00	
Fuel life cycle (A)	1.30E-01	1.94E-04	6.50E-07	1.17E+00	7.67E-02	1.85E-04	6.49E-07	8.71E-01	GWP=5.30E-02
Vehicle materials (B)	5.02E-02	2.95E-04	4.19E-07	5.96E-01	5.02E-02	2.95E-04	4.19E-07	5.96E-01	WC=9.00E-06
Total life cycle impact (C=A+B)	1.80E-01	4.90E-04	1.07E-06	1.77E+00	1.27E-01	4.80E-04	1.07E-06	1.47E+00	LU=0.00E+00
Life cycle impact of gasoline (D)	2.53E-01	6.19E-04	1.90E-07	2.92E+00	2.53E-01	6.19E-04	1.90E-07	2.92E+00	FFD=3.00E-01
Reduction compared to gasoline [(E-D)/E]	29%	-	-	39%	50%	-	-	50%	

3. Environmental strategies for PHEV:

- Strategy 1: Use of E10 (10% ethanol and 90% gasoline) in place of gasoline as fuel

Item	Base case				After implementing strategy				Reduction from base case
	GWP (kgCO_2)	WC (m^3)	LU (ha.a)	FFD (MJ)	GWP (kgCO_2)	WC (m^3)	LU (ha.a)	FFD (MJ)	$C_{base\ case}$- $C_{after\ implementing\ strategy}$ GWP= 8.00E-03 WC= -3.20E-05 LU= -5.70E-08 FFD=7.00E-02
Fuel (base case gasoline and E10 is the strategy) for 1 Litre	7.25E-01	7.39E-03	1.45E-06	4.46E+01	7.00E-01	8.69E-03	3.98E-06	4.08E+01	
Fuel life cycle (A)	1.79E-01	2.66E-04	3.73E-07	1.61E+00	1.71E-01	2.98E-04	4.30E-07	1.53E+00	
Vehicle materials (B)	3.83E-02	2.69E-04	2.50E-07	3.96E-01	3.83E-02	2.69E-04	2.50E-07	3.96E-01	
Total life cycle impact (C=A+B)	2.17E-01	5.35E-04	6.23E-07	2.00E+00	2.09E-01	5.67E-04	6.80E-07	1.93E+00	
Total life cycle impact of gasoline (D)	2.53E-01	6.19E-04	1.90E-07	2.92E+00	2.53E-01	6.19E-04	1.90E-07	2.92E+00	
Reduction compared to gasoline [(D-C)/D]	14.11%	-	-	31.36%	17.31%	-	-	34%	

- Strategy 1 and 2: Use of E10 in place of gasoline as fuel +Cleaner grid electricity (2030 grid of WA as like EV) for charging

Item	Base case				After implementing strategy				Reduction from base case
	GWP (kgCO_2)	WC (m^3)	LU (ha.a)	FFD (MJ)	GWP (kgCO_2)	WC (m^3)	LU (ha.a)	FFD (MJ)	$C_{base\ case}$- $C_{after\ implementing\ strategy}$ GWP= 3.90E-02 WC= -1.80E-05 LU= -5.60E-08 FFD=2.30E-01
Fuel life cycle (A)	1.79E-01	2.66E-04	3.73E-07	1.61E+00	1.40E-01	2.84E-04	4.29E-07	1.37E+00	
Vehicle materials (B)	3.83E-02	2.69E-04	2.50E-07	3.96E-01	3.83E-02	2.69E-04	2.50E-07	3.96E-01	
Total life cycle impact (C=A+B)	2.17E-01	5.35E-04	6.23E-07	2.00E+00	1.78E-01	5.53E-04	6.79E-07	1.77E+00	
Total life cycle impact of gasoline (D)	2.53E-01	6.19E-04	1.90E-07	2.92E+00	2.53E-01	6.19E-04	1.90E-07	2.92E+00	
Reduction compared to gasoline base case [(D-C)/D]	14.11%	-	-	31.36%	30%	-	-	39%	

- Strategy 1, 2 and 3: Cleaner grid electricity for charging + Use of E10 in place of gasoline+ Placement of 180 W_p solar PV on the vehicle

Item	Base case				After implementing strategy				Reduction from base case
	GWP ($kgCO_2$)	WC (m^3)	LU (ha.a)	FFD (MJ)	GWP ($kgCO_2$)	WC (m^3)	LU (ha.a)	FFD (MJ)	
Fuel life cycle (A)	1.79E-01	2.66E-04	3.73E-07	1.61E+00	1.27E-01	2.58E-04	4.17E-07	1.25E+00	$C_{\text{base case}}$- $C_{\text{after implementing strategy}}$
Vehicle materials (B)	3.83E-02	2.69E-04	2.50E-07	3.96E-01	3.83E-02	2.69E-04	2.50E-07	3.96E-01	GWP= 5.20E-02 WC= 8.00E-06 LU= -5.00E-09 FFD=3.50E-01
Total life cycle impact (C=A+B)	2.17E-01	5.35E-04	6.23E-07	2.00E+00	1.65E-01	5.27E-04	6.67E-07	1.61E+00	
Total life cycle impact of gasoline (D)	2.53E-01	6.19E-04	1.90E-07	2.92E+00	2.53E-01	6.19E-04	1.90E-07	2.92E+00	
Reduction compared to gasoline base case [(D-C)/D]	14.11%	-	-	31.36%	34.70%	-	-	43.57%	

4. Environmental strategies for E65:

- Strategy: Ethanol blend E55 is considered in place of E65

(i) Environmental impact of different ethanol feedstocks used in the study:

Item	GWP ($kgCO_2$)	WC (m^3)	LU (ha.a)	FFD (MJ)
E_{Wheat} , 1L	9.34E-01	1.07E-02	5.29E-04	1.14E+01
E_{Straw} , 1 L	4.60E-01	1.60E-02	2.67E-05	5.93E+00
E_{Mallee} ,1 L	4.65E-01	1.48E-02	3.56E-04	6.16E+00
Gasoline, 1 L	7.25E-01	7.39E-03	1.45E-06	4.46E+01

(ii) Changes in environmental impact due to the switch from E65 to E55

Item	E65				E55			
	GWP ($kgCO_2$)	WC (m^3)	LU (ha.a)	FFD (MJ)	GWP ($kgCO_2$)	WC (m^3)	LU (ha.a)	FFD (MJ)
1 L (E65 = 10% E_{Wheat} + 53% E_{Straw} + 2% E_{Mallee} + 35% Gasoline) (E55 = 0% E_{Wheat} + 53% E_{Straw} + 2% E_{Mallee} + 35% Gasoline)	6.00E-01	1.24E-02	7.47E-05	2.00E+01	5.55E-01	1.21E-02	2.20E-05	2.31E+01
Fuel per km with combustion and transportation to retailer (E65 fuel consumption: 0.075 L/km, E55 fuel consumption: 0.072 L/km) (A)	1.30E-01	9.36E-04	5.61E-06	1.51E+00	1.46E-01	8.77E-04	1.58E-06	1.69E+00
Vehicle materials (B)	1.96E-02	1.81E-04	1.09E-07	2.30E-01	1.96E-02	1.81E-04	1.09E-07	2.30E-01
Total (A+B)	1.49E-01	1.12E-03	5.72E-06	1.74E+00	1.66E-01	1.06E-03	1.69E-06	1.93E+00

5. Social strategy in regard to Job creation indicator

- Strategy: Job creation due to local battery production

Based on Boston Energy and Innovation Australia (Steen et al., 2017) and by considering standard 34.4 working hours per week for Australia (Rustandi and Wu, 2010), 1.50E+07 kWh battery production requires 3.98E+06 direct man-hours (i.e. 15 GWh/year requires 2222.2 direct employment) for Li-ion battery production.

Fuel options	Battery size, kWh (a)	Job creation, man-hours/kWh (b)	Total Job creation, man-hours (c=a*b)	Total km of vehicle [2] (d)	Job creation, man-hours/km for local battery production (e= c/d)
EV	40	3.98E+06 man-hours ÷ 1.50E+07 kWh = 2.65E-01 man-hours/kWh	1.06E+01	1.13E+05	9.42E-05
PHEV	8.8		2.33E+00		2.07E-05
Hydrogen	1.6		4.24E-01		1.84E-10

6. Economic analysis for E55

Ethanol from straw (for 1 L ethanol):

Item	Unit for items	Required amount for 1 L ethanol	Unit cost in AUD	Total Cost in AUD (After allocation within electricity i.e., ethanol 91% and electricity 9%)
Nutrient replacement for straw removal (4.32 kg straw for 1 L ethanol)	kg	4.32E+00	1.51E-02	5.94E-02
Incentive to growers for bioenergy initiative	kg	4.32E+00	11 AUD/kg	4.33E-02
Diesel requirement for straw harvest	L	3.55E-04	1.48E+00	4.78E-04
Contractor cost for straw harvest	kg	4.32E+00	2.45E-03	9.62E-03
Straw bailing	Kg	4.32E+00	2.20E-02	8.66E-02
On farm cartage and handling	Kg	4.32E+00	9.92E-03	3.90E-02
Storage	Kg	4.32E+00	1.10E-02	4.33E-02
Straw transportation to plant 4.32 kg	kg	4.32E+00	27 AUD/tonne	1.08E-01
Ethanol production				
Make up water consumption	kg	7.86E+00	7.22E-03	5.17E-02
Enzyme	kg	2.11E-02	6.42E+00	1.23E-01
Lime	kg	9.66E-02	4.00E-01	3.52E-02
sulfuric Acid	kg	4.25E-02	6.88E-01	2.66E-02
Corn steep liquor (heat from natural gas)	kg	4.25E-02	3.00E-01	1.16E-02
DAP	kg	5.31E-03	5.61E-04	2.71E-06
wastewater treatment chemical (10% urea 90% NaOH)	kg	1.86E-03	6.50E-01	1.10E-03
Transportation of lime (lanceline to Northam)	tkm	1.74E-02	3.20E-01	5.07E-03
Transportation of sulfuric acid from kwinana to plant	tkm	5.52E-03	3.20E-01	1.61E-03
Transportation of corn steep liquir from NSW to Kwinana	tkm	1.44E-01	3.20E-01	4.20E-02
Transportation of corn steep liquir from kwiana to plant	tkm	5.52E-03	3.20E-01	1.61E-03
DAP from Kwinana to plant	tkm	6.90E-04	3.20E-01	2.01E-04
waste treatment chemical from Kwinana to paddock	tkm	2.42E-04	3.20E-01	7.06E-05
Combustion bottom ash to landfill	kg	1.93E-01	6.00E+01 per tonne	1.05E-02
Combustion bottom gypsum to landfill	kg	1.13E-01		6.19E-03

Transportation of ash and gypsum to landfill	tkm	2.72E-02	3.20E-01	7.93E-03
Plant cost with maintenance	-	-	-	1.72E-01
Labour	-	-	-	3.79E-02
Ethanol transported back to Kwinana for blending	tkm	1.10E-0	6.90E-02	7.59E-03
Producer profit margin	-	-	-	1.00E-01
Total for 1 L ethanol				1.01E+00

Ethanol (per L) from wheat:

Item	Unit	Required amount for 1 L ethanol	Unit cost in AUD	Total Cost in AUD (After allocation with DDGS i.e., ethanol 79.47% and DDGS 20.53%)
Feedstock*	kg	2.50E+00	2.03E-01	4.03E-01
Feedstock transportation from plant to farm	tkm	3.25E-01	1.40-01	3.62E-02
Electricity required for milling and pumping	kWh	1.00E-01	3.24E-01	2.58E-02
Heat required for liquefaction and distillation	MJ	5.10E+00	9.81E-03	3.98E-02
Water	L	3.10E-01	3.65E-03	9.00E-04
Plant cost with maintenance	-	-	-	7.72E-02
Labour	-	-	-	2.34E-02
Producer profit margin	-	-	-	1.00E-01
Total for 1 L ethanol				7.1E-01

- Based on long term contract with the ethanol plant and wheat (lower grade starch) producer (AECOM Australia, 2016)

Ethanol from Mallee (1 L ethanol) :

Item	Unit for items	Required amount for 1 L ethanol	Unit cost in AUD	Total Cost in AUD (After allocation within electricity i.e., ethanol 91% and electricity 9%)
Mallee Plant establishment	kg	5.80	3.72 AUD per tonne	1.97E-02
Malle management after every harvest				
Urea	kg	4.23E-03	5.30E-01	2.04E-01
DAP	kg	4.23E-03	5.60E-01	2.16E-01

Muriate of potash as Potassium chloride	kg	1.69E-03	5.00E-01	7.70E-02
Diesel	L	8.46E-04	1.48E+00	1.14E-01
Diesel transportation from kwiana to paddock	tkm	2.07E-04	3.20E-01	6.03E-03
Transportation of fertilizer from kwinana to paddock	tkm	3.00E-03	3.20E-01	8.72E-02
Contractor work for fertilizer spraying 0.5 hour				1.15E-01
Land opportunity cost			21.84 AUD/tonne	1.15E-01
Mallee harvest, haulage and shunting				
Diesel	L	2.03E-02	1.48E+00	2.74E-02
Diesel transport	tkm	4.99E-03	3.20E-01	1.45E-03
Cost of harvester	kg	5.80E-01	11.41 AUD/tonne	6.02E-02
Rent for the harvesting person	kg	5.80E-01	5.11 AUD/tonne	2.70E-02
Ethanol production				
Wood transportation to plant (100 km)	tkm	5.80E-01	2.00E-01	1.06E-01
Supply chain management and transportation	kg	5.80	4.35 AUD/tonne	2.29E-02
Water	kg	4.42E+00	8.56E-03	3.44E-02
Enzyme	kg	2.11E-02	6.42E+00	1.23E-01
lime	kg	8.33E-02	4.00E-01	3.03E-02
sulfuric Acid	kg	1.14E-01	6.88E-01	7.16E-02
Corn steep liquor	kg	4.48E-02	3.00E-01	1.22E-02
DAP	kg	5.29E-03	5.60E-01	2.69E-03
wastewater treatment chemical (10% urea 90% NaOH)	kg	1.88E-03	6.60E-01	1.13E-03
Transportation of corn steep liquor from NSW to Kwinana	tkm	1.52E-01	3.20E-01	4.43E-02
Transportation of acid, DAP, NaOH to the plant	tkm	6.04E-02	3.20E-01	1.76E-02
ash land fill	kg	1.20E-01	6.00E-02	6.55E-03
gypsym fill	kg	7.28E-02	6.00E-02	3.97E-03
transport ash and gypsum to landfill	tkm	9.64E-03	3.20E-01	2.81E-03
Labour cost				3.79E-02
plant cost				1.71E-01
ethanol transported to Kwinana blending station	tkm	1.03E-01	6.90E-02	7.08E-03
Producer profit margin				1.00E-01
Total for 1 L ethanol				1.11E+00
Total with excise rate in WA	1.09E-01 AUD/L			1.14E+00

Gasoline price without GST according to fuel watch WA= 1.11E+00 AUD/L (last 7 year average as mentioned in Chapter 6)

Price for E55 as mentioned in Chapter 6 = (45% gasoline price + 53% straw based ethanol + 2% Mallee based ethanol) + 10% GST

7. Economic strategies for E55 in regard to life cycle cost indicator

- Strategy 1: Removal of excise rate on ethanol
- Strategy 2: Long term soft loan for the capital cost at the rate of 3% interest rate over the project life
- Strategy 3: 10% of capital (around 19 M AUD) subsidy from the government
- Strategy 3: Removal of GST on E55

Item	Before implementing strategies, AUD/VKT	After implementing strategy 1, AUD/VKT	After implementing strategies 1 and 2, AUD/VKT	After implementing strategies 1, 2 and 3 AUD/VKT	After implementing strategies 1, 2, 3 and 4 AUD/VKT
Cost of E 55 (A)	1.00E-01	9.00E-02	9.00E-02	9.00E-02	8.00E-02
Additional vehicle cost (B)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total life cycle cost (C=A+B)	1.00E-01	9.00E-02	9.00E-02	9.00E-02	8.00E-02
Total cost for gasoline (D)	8.13E-02	8.13E-02	8.13E-02	8.13E-02	8.13E-02
Reduction compared to gasoline [(D-C)]	-2.00E-02	-1.00E-02	-1.00E-02	-1.00E-02	0.00E+00

8. Economic strategies for hydrogen fuel in regard to life cycle cost indicator

Strategies for Fuel

- Strategy 1: With the soft loan scheme and 10% capital subsidy
- Strategy 2: Removal of GST on hydrogen purchase
- Strategy 3: Utilization of product oxygen
- Strategy 4: hydrogen production plant received electricity at a rate of 8.3 cents/kWh through power purchase agreements (PPAs)

Item	Before implementing strategies, AUD/VKT	After implementing strategy 1, AUD/VKT	After implementing strategy 1 and 2, AUD/VKT	After implementing strategy 1, 2 and 3, AUD/VKT	After implementing strategy 1, 2 and 3 and 4, AUD/VKT
Cost of hydrogen fuel (A)	3.07E-01	3.03E-01	2.76E-01	2.64E-01	8.13E-02
Additional vehicle cost (B)	4.81E-01	4.81E-01	4.81E-01	4.81E-01	4.81E-01
Total life cycle cost (C=A+B)	7.87E-01	7.84E-01	7.56E-01	7.44E-01	5.62E-01
Total cost for gasoline (D)	8.13E-02	8.13E-02	8.13E-02	8.13E-02	8.13E-02
Reduction compared to gasoline [(D-C)]	-7.06E-01	-7.03E-01	-6.75E-01	-6.63E-01	-4.81E-01

9. Economic strategies for PHEV in regard to life cycle cost indicator

Strategies for Fuel: No economic strategies for fuel but fuel cost changes due to environmental strategies (i.e.: 6.6% mileage from solar PV)

Alternative fuel Vehicle

- Strategy V1: Removal of GST on vehicle purchase
- Strategy V2: Fifty percent subsidy on vehicle registration
- Strategy V3: Inclusion of import duty on gasoline
- Strategy V4: direct subsidy and/or with the tax benefits

Item	Before implementing strategies, AUD/VKT	After implementing fuel strategies, AUD/VKT	After implementing both fuel and vehicle strategy V1, AUD/VKT	After implementing both fuel and vehicle strategies V1 and V2, AUD/VKT	After implementing both fuel and vehicle strategies V1, V2 and V3, AUD/VKT	After implementing both fuel and vehicle strategies V1, V2, V3 and V4 AUD/VKT
Cost of liquid fuel (base case gasoline) (A)	3.00E-02	2.60E-02	2.60E-02	2.60E-02	2.60E-02	2.60E-02
Cost of electricity (B)	1.30E-02	1.30E-02	1.30E-02	1.30E-02	1.30E-02	1.30E-02
Additional vehicle cost (C)	1.65E-01	1.65E-01	9.90E-02	6.60E-02	5.50E-02	4.10E-02
Total life cycle cost (D=A+B+C)	2.08E-01	2.04E-01	1.38E-01	1.05E-01	9.40E-02	8.00E-02
Total cost for gasoline (E)	8.13E-02	8.13E-02	8.13E-02	8.13E-02	8.13E-02	8.13E-02
Reduction compared to gasoline [(E-D)]	-8.90E-02	-8.70E-02	-5.50E-02	-1.90E-02	-1.00E-02	0.00E+00

Appendix-F

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Figure A-1 and A-2 in appendix chapter:

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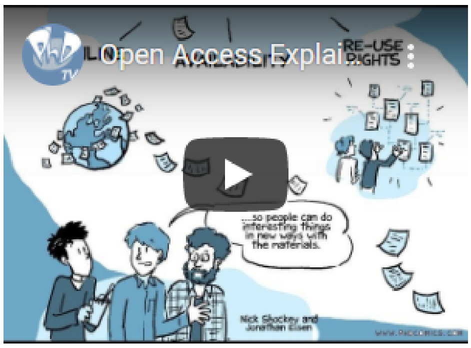

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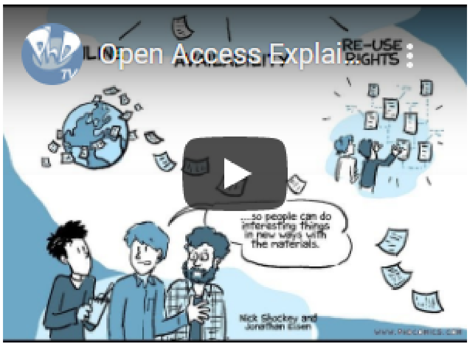

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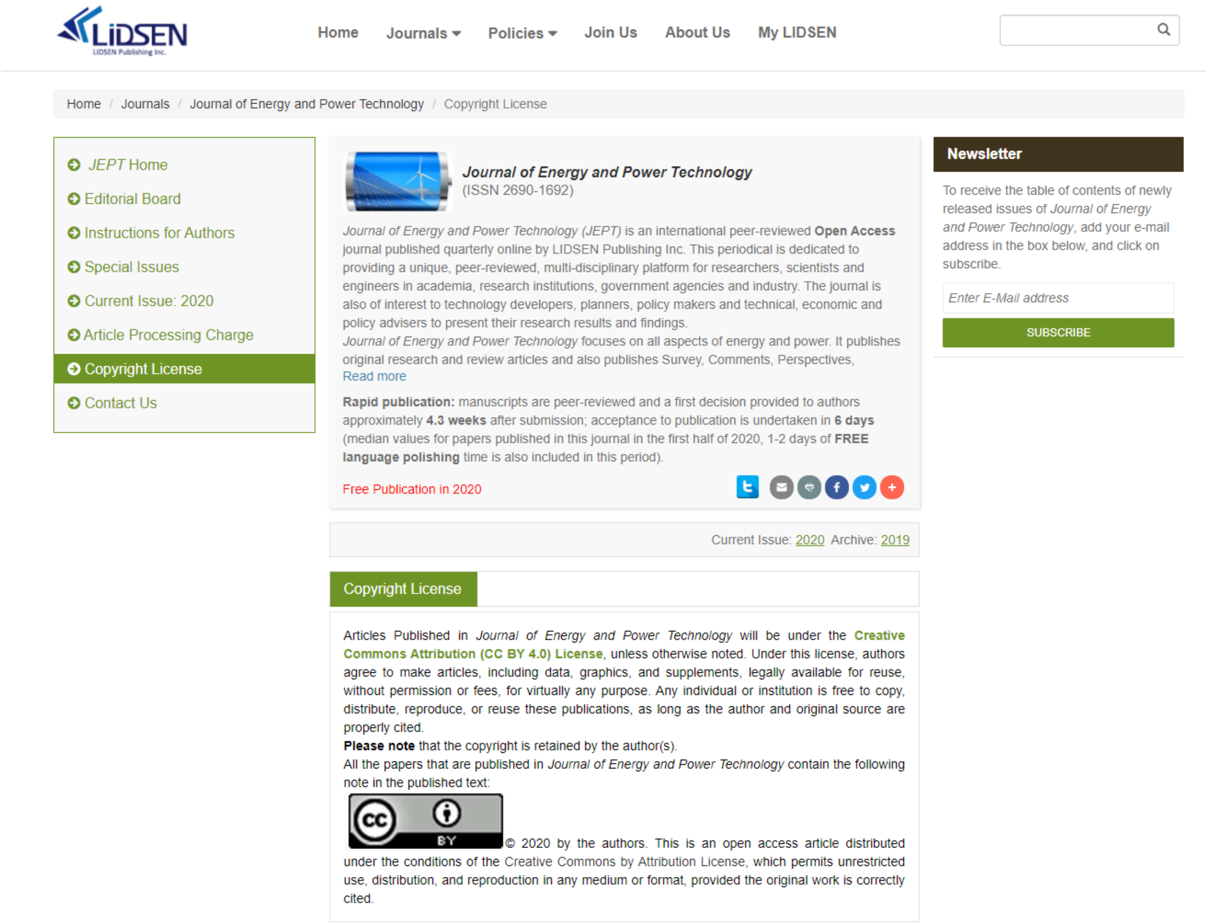

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